Nuclear Astrophysics at NIF
- Hydrogen Burning and Electron Screening

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Nuclear Processes in the cosmos

energy production

binding energy/nucleon

$\Delta m \sim 0.8\ \%\ m_{nucleon}$

$4\,H \rightarrow {}^4He + 2\,e^+ + 2\,\nu + 26\ MeV$

using 10 % of its inventory

“our“ sun shines ~ 10 Billion years

nucleosynthesis

many scenarios:

- big bang nucleosynthesis
- static burning (hydrogen and helium)
- advanced burning processes (i.e.hot CNO) $\longrightarrow$ iron + s-process elements
- explosive burning (r- and rp-process) $\longrightarrow$ uranium; r + p elements

sufficient for evolution

produced the elements in our body

we exist on earth

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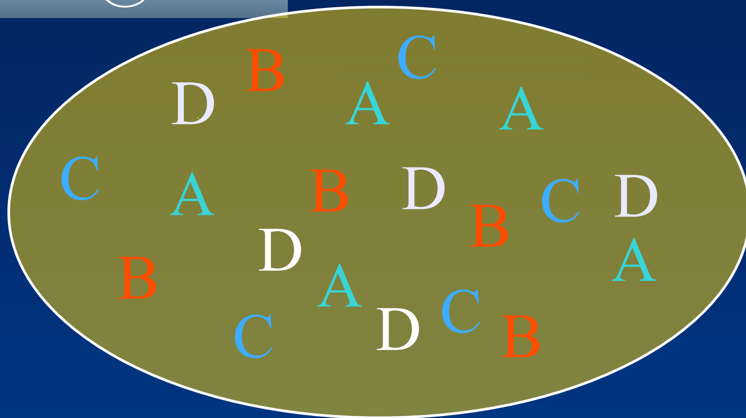


Astrophysical Scenario

- abundances
- temperature T

probability for a nuclear reaction: $A + B \longrightarrow C + D$

$\sigma_{AB}(v)$	**cross section**

to be provided by the "Nuclear Astrophysicist"

For a given temperature T, we fold the energy dependant probability for the nuclear reaction with the characteristic Maxwell-Boltzmann distribution of the particle velocities.

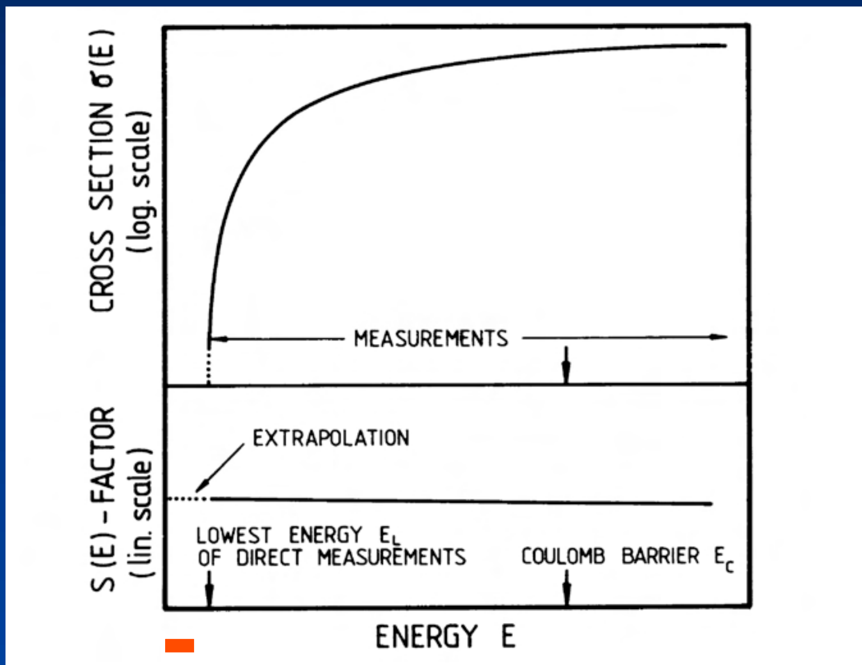
$$\langle\sigma v\rangle = [8/\pi\mu(kT)^3]^{1/2} \int_0^{\infty} E\, \sigma(E) \exp(-E/kT)\, dE$$

stellar reaction rate

Stellar temperatures T $\Rightarrow$ Laboratory energies

static $\rightarrow$ explosive scenarios — a few **keV** $\rightarrow$ **MeV**

Reactions with charged particles: non-resonant



Stellar energies

Parametrisation of cross section:

$$\sigma(E) \;=\; S(E) \;\; 1/E \;\; \exp(-2\pi\eta)$$

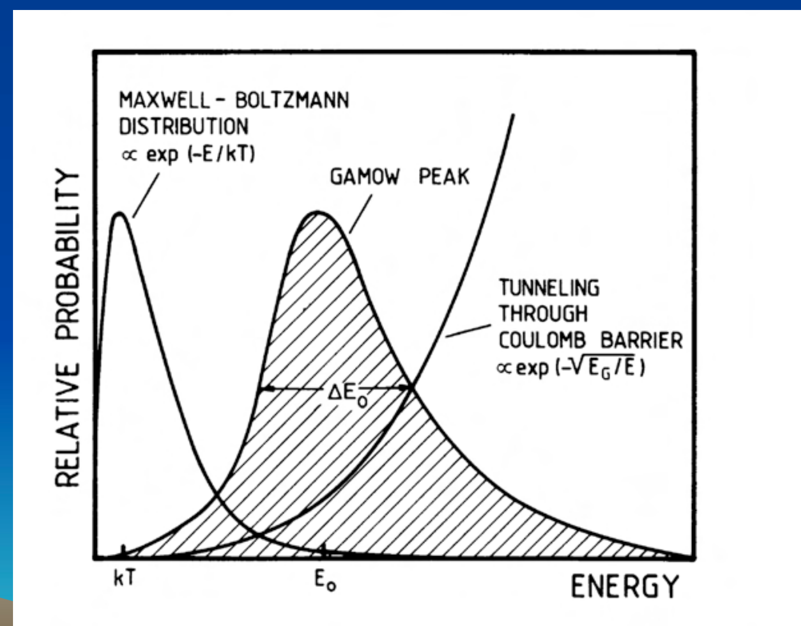
Astrophysical S-factor

Geometrical factor

Gamow factor

Stellar reaction rate

$<\sigma v>$



We have to determine the cross section within the Gamow peak, around E_0, not down to kT

Static Burning and NIF

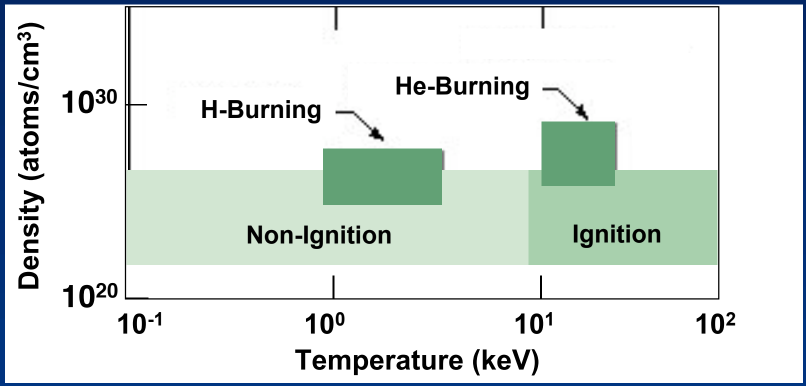


Figure borrowed from L. Bernstein

How does an assumed energy range for NIF (2-12 keV) translate in terms of temperature and Gamow energy?

$^{3}He(^{4}He,\gamma)^{7}Be$

Ion T [keV]	Ion T [E6 K]	EG [keV]	DeltaG [keV]
2	23.2018561	29.9301835	17.8697286
3	34.8027842	39.2196355	25.0530539
4	46.4037123	47.5112048	31.8402367
5	58.0046404	55.1318695	38.3472859
6	69.6055684	62.2572906	44.6394673
7	81.2064965	68.9956022	50.7584082
8	92.8074246	75.4193366	56.7328521
9	104.408353	81.5801293	62.5837697
10	116.009281	87.5163876	68.3270957
11	127.610209	93.2576584	73.9753222
12	139.211137	98.8272886	79.5384883

$^{6}Li(p,\gamma)^{7}Be$

Ion T [keV]	Ion T [E6 K]	EG [keV]	DeltaG [keV]
2	23.2018561	19.6098177	14.4643874
3	34.8027842	25.6961305	20.2788238
4	46.4037123	31.1286453	25.7726084
5	58.0046404	36.1215931	31.0396432
6	69.6055684	40.7900646	36.1327563
7	81.2064965	45.2049077	41.0856425
8	92.8074246	49.4136443	45.9215676
9	104.408353	53.4501055	50.6575063
10	116.009281	57.3394549	55.3063566
11	127.610209	61.1010514	59.87823
12	139.211137	64.7501915	64.3812525

$^{17}O(p,\gamma)^{18}F$

Ion T [keV]	Ion T [E6 K]	EG [keV]	DeltaG [keV]
2	23.2018561	38.948773	20.3849738
3	34.8027842	51.0373308	28.5793846
4	46.4037123	61.8273232	36.3218941
5	58.0046404	71.7442533	43.7448399
6	69.6055684	81.0167126	50.9226743
7	81.2064965	89.7854183	57.9028839
8	92.8074246	98.1447579	64.7182577
9	104.408353	106.161926	71.3927185
10	116.009281	113.886903	77.9444436
11	127.610209	121.358139	84.3876835
12	139.211137	128.606015	90.7338905

T_6 = 20 - 140 Kelvin

Gamow energies: 20 - 130 keV

(these are the accelerator energies to compare to)

(Preselected reactions with radioactive product)

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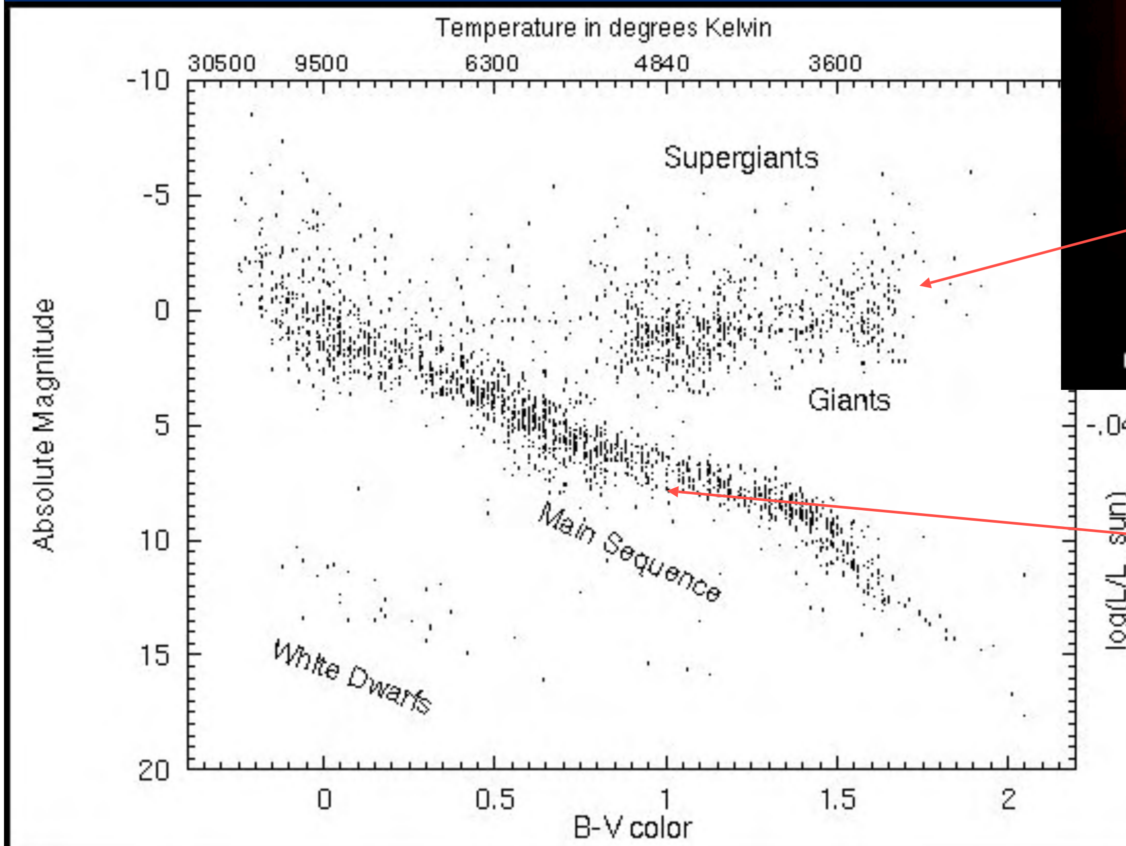
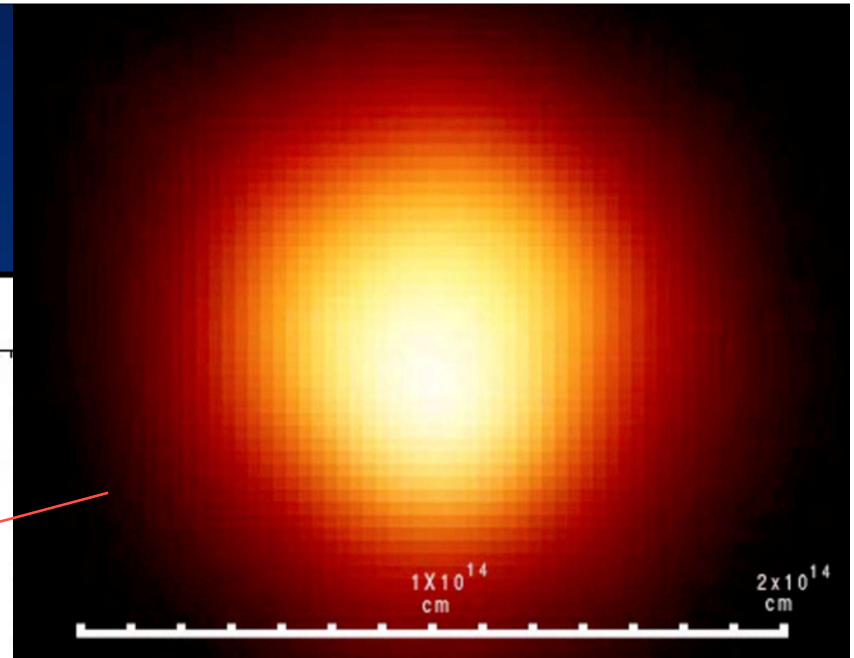
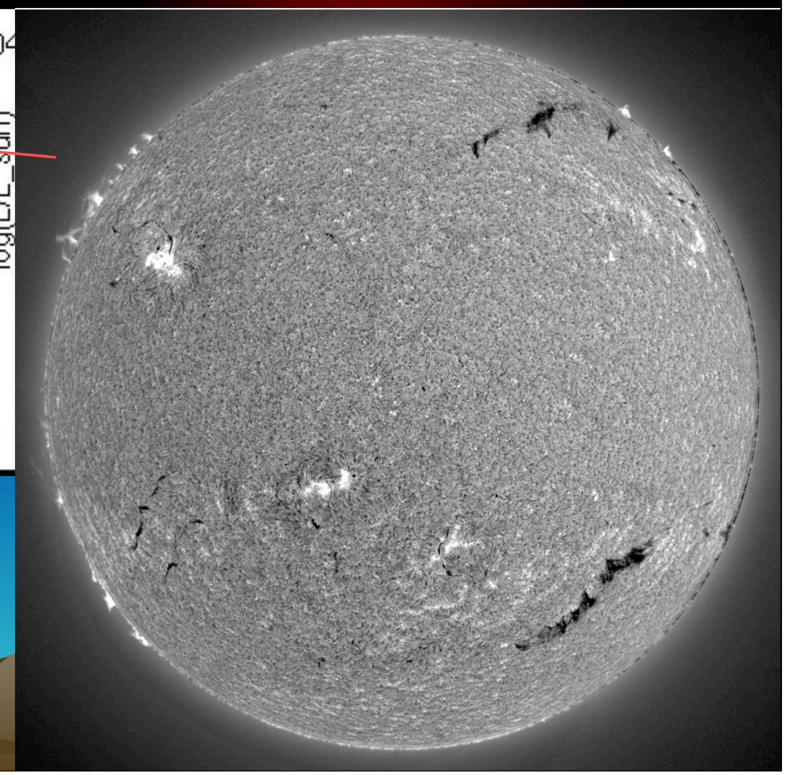
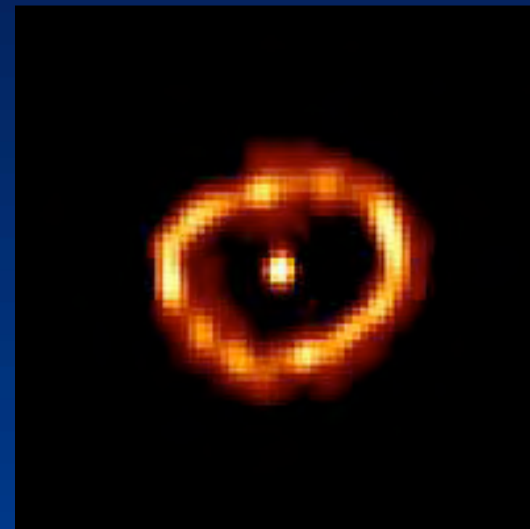
Stable Burning Phases







What about explosive scenarios?



NIF energy range could be relevant for novae and Big Bang?

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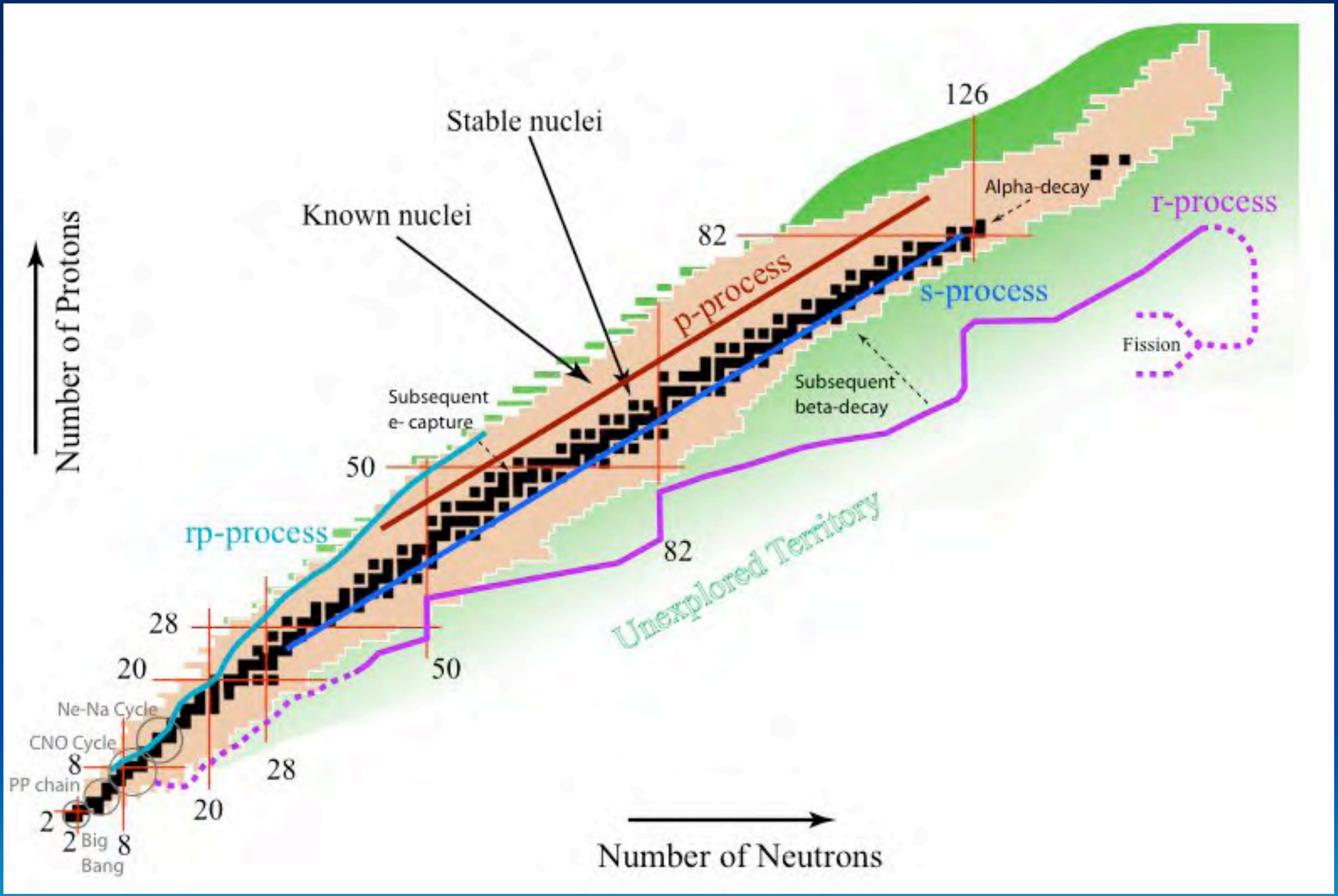

Courtesy of Frank Timmes

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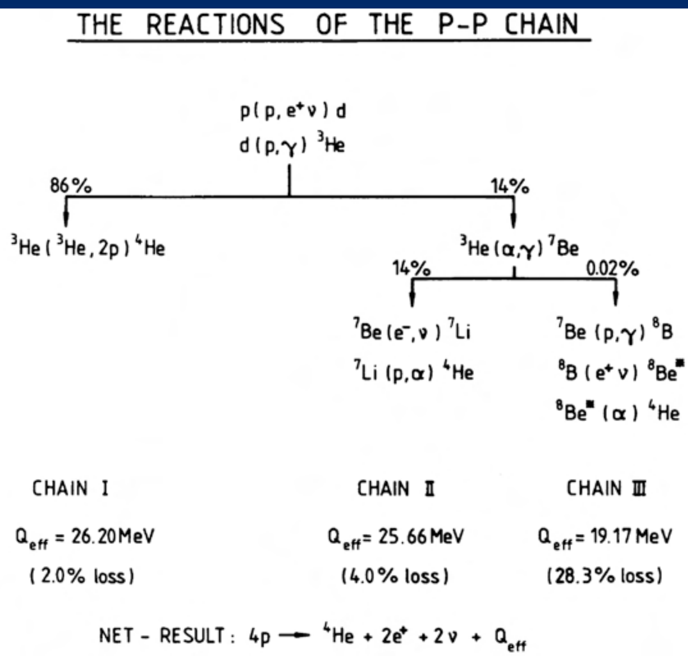
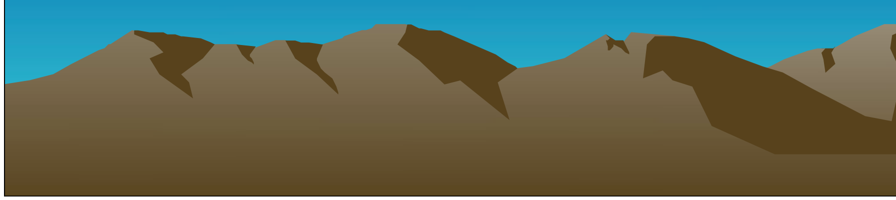
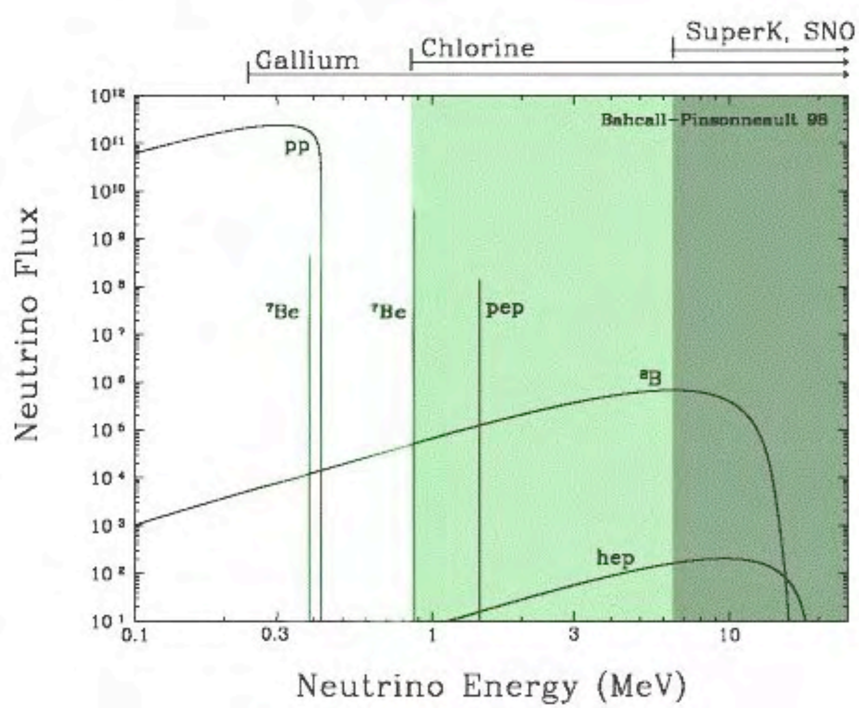
Solar hydrogen burning

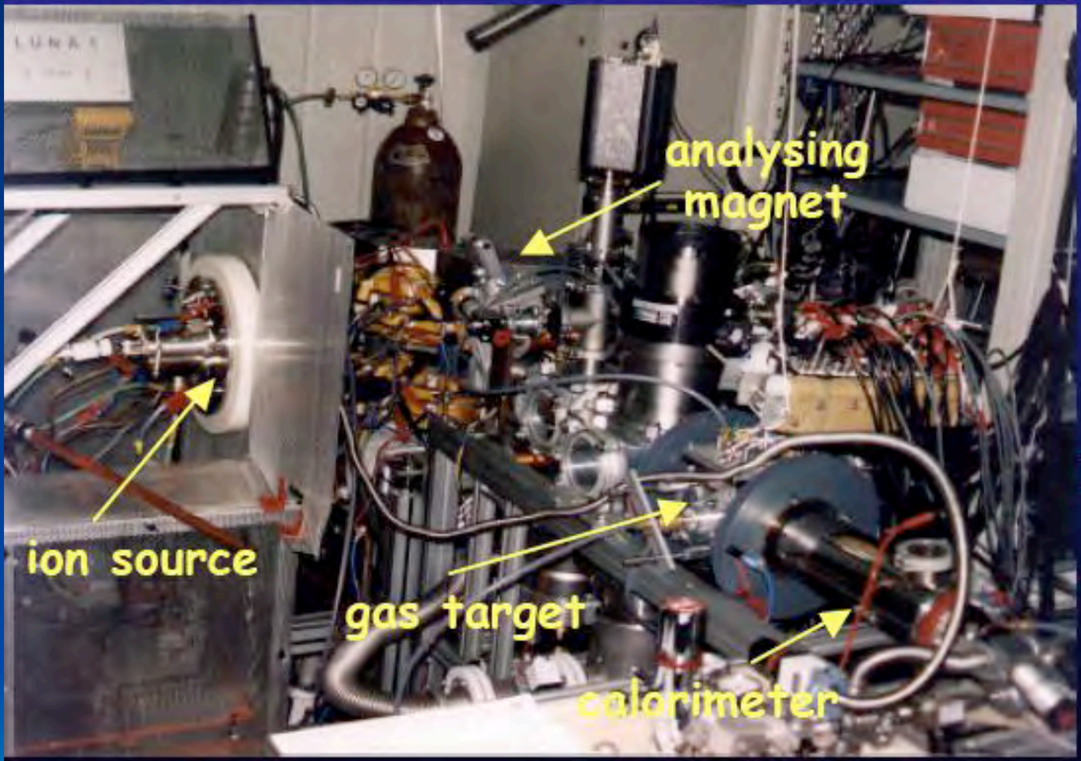






State of the Art in Nuclear Astrophysics

LUNA1 (50 kV)



Voltage Range :
1 - 50 kV

Output Current:
1 mA

Beam energy spread:
20 eV

Long term stability (8 h):
10^{-4}

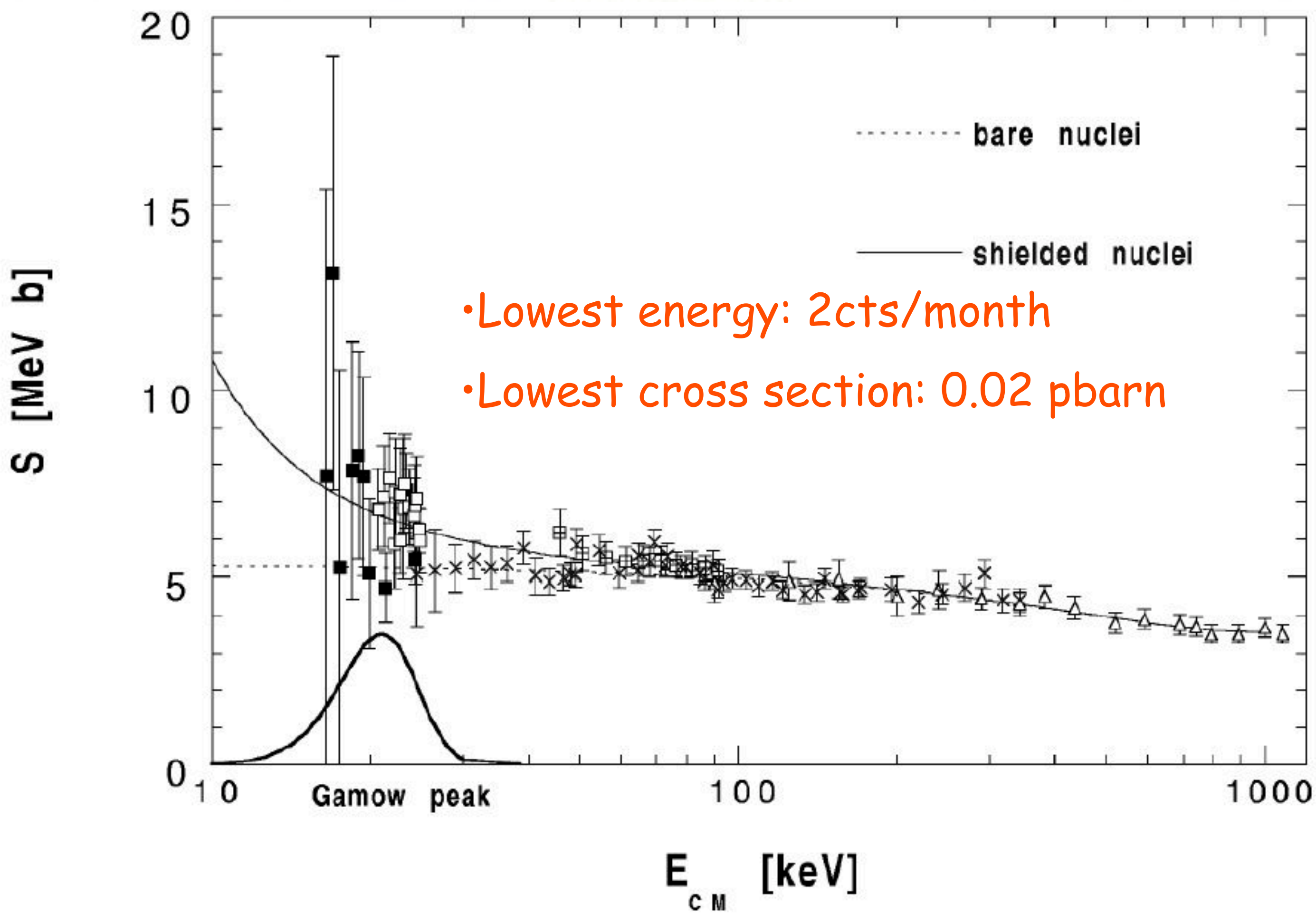
Terminal Voltage ripple:
$5\ 10^{-5}$

nuclear

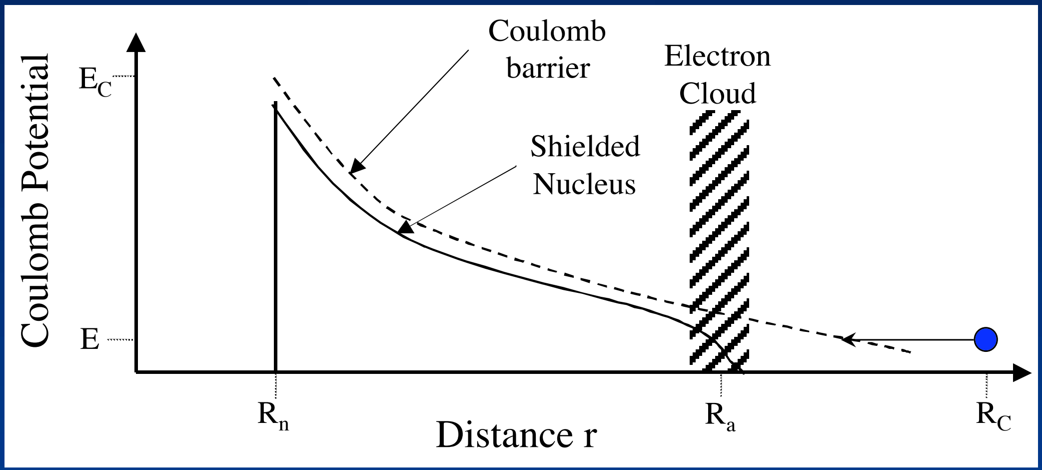
VOLUME 82, NUMBER 26 PHYSICAL REVIEW LETTERS 28 JUNE 1999

First Measurement of the $^3He(^3He, 2p)^4He$ Cross Section down to the Lower Edge of the Solar Gamow Peak

R. Bonetti,[1] C. Broggini,[2,*] L. Campajola,[3] P. Corvisiero,[4] A. D'Alessandro,[5] M. Dessalvi,[4] A. D'Onofrio,[6] A. Fubini,[7] G. Gervino,[8] L. Gialanella,[9] U. Greife,[9] A. Guglielmetti,[1] C. Gustavino,[5] G. Imbriani,[3] M. Junker,[5] P. Prati,[4] V. Roca,[3] C. Rolfs,[9] M. Romano,[3] F. Schuemann,[9] F. Strieder,[9] F. Terrasi,[3] H. P. Trautvetter,[9] and S. Zavatarelli[4]
(LUNA Collaboration)



Electron Screening in Nuclear Reactions



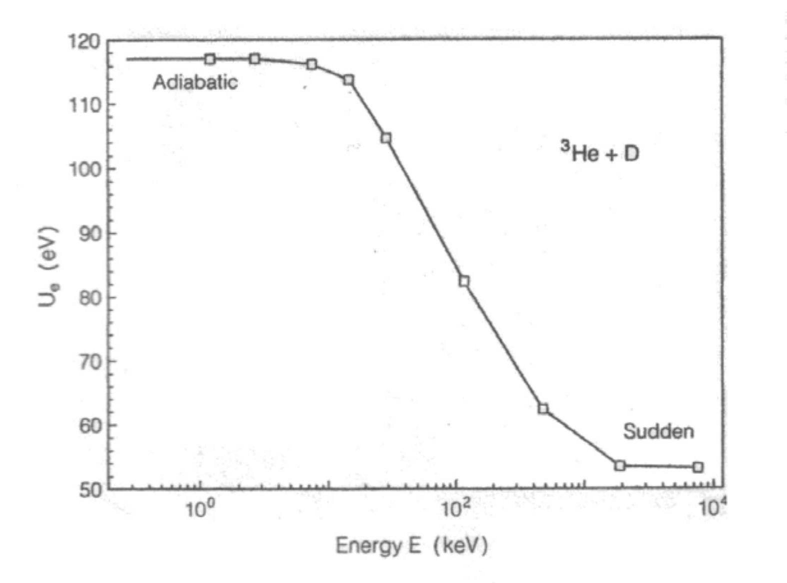
Usually experimentalists use a simple model: all participating electrons at atomic radius on surface

Screening potential:

$$U_e = Z_1 Z_2 e^2 / R_a$$

Better theoretical approach uses the differences in electron binding energy before and after the nuclear reaction: "adiabatic limit"

$\text{velocity}_{\text{nuclei}}$ << $\text{velocity}_{\text{electrons}}$



$\text{velocity}_{\text{nuclei}}$ >> $\text{velocity}_{\text{electrons}}$

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48 *H. Costantini et al. / Physics Letters B 482 (2000) 43–49*

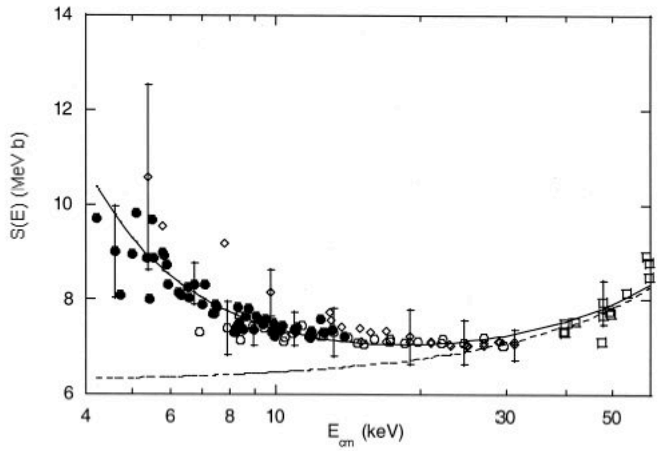
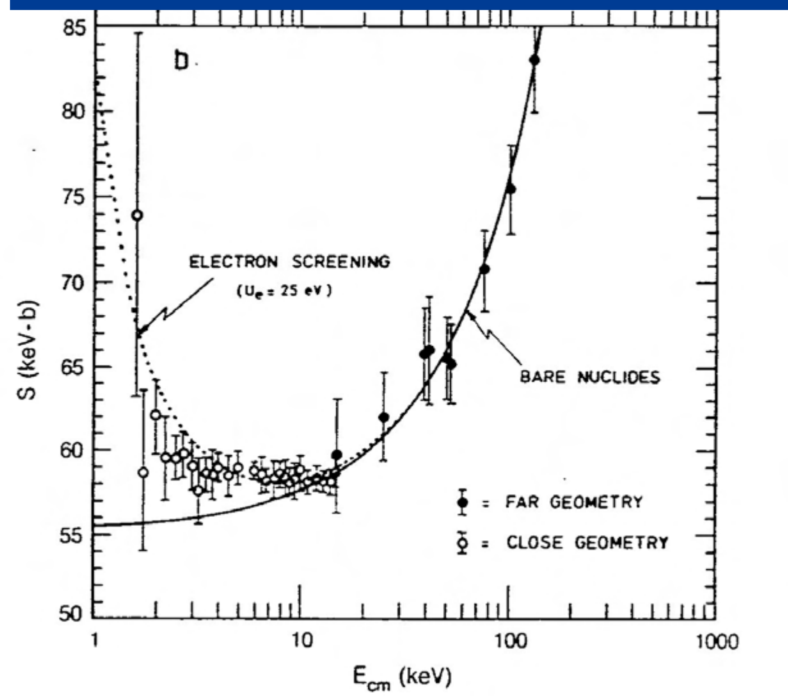


Fig. 2. $S(E)$ factor data for the d(^{3}He,p)^{4}He reaction from previous work ([4]: open points; [7] : open diamonds; [18] : open squares), normalized by a fitting procedure, and present work (filled-in points). Accidental and systematical errors, added in quadratures, are shown only for a few points. The dashed curve represents the $S(E)$ factor for bare nuclei and the solid curve that for shielded nuclei with U_e = 132 eV.

Examples of Electron Screening in the Accelerator Laboratory

D(d,p)t (Bochum)



D(^{3}He,p)^{4}He (Bochum, LUNA)

Enhancement factor f_{lab}

$$f(E) = \sigma_{\rm exp}(E)/\sigma_{\rm bn}(E) = \sigma(E+U_e)/\sigma(E).$$

Often approximated as

$$f(E) \approx \exp\left\{\pi\eta(E)\frac{U_e}{E}\right\}.$$ with $$\eta = \frac{Z_1 Z_2 e^2}{h\nu}$$

Experimental data of U_e

Reactions	U_e (eV)		References
	adiabatic	experimental	
$d(d,p)t$	14	25 ± 5	Greife et al. (1995)
$^{3}He(d,p)^{4}He$	120	186 ± 12	Prati et al. (1994)
$d(^{3}He,p)^{4}He$	65	123 ± 9	Prati et al. (1994)
$^{7}Li(p,\alpha)^{4}He$	182	300 ± 280	Engstler et al. (1992)
$^{11}B(p,\alpha)^{8}Be^{+}$	348	430 ± 80	Angulo et al. (1993)

experimental U_e >> adiabatic U_e

Problem exists; but at NIF we would be looking at an even different physics case:

Electron screening in a dense plasma

Slide borrowed from F.Raiola

Debye - Hückel screening (weak screening)

In a plasma the electrons are on average distributed on a radius…

$$R_D = \sqrt{\frac{kT}{4\pi e^2 \rho N_A \xi}}$$

with

$$\xi = \sum_i (Z_i^2 + Z_i)^2 Y_i$$

… this leads to an additonal electron screening potential term….

$$U(r) = U(0) = U_0 = -\frac{e^2 Z_1 Z_2}{R_D}$$

… and we can calculate an enhancement factor

$$f = 1 + 0.188\, Z_1 Z_2 \rho^{1/2} \xi^{1/2} T_6^{-3/2}$$

kT [keV]	U_0 [keV]	f_{D-H}	f_{LAB}
2	0.44279979	1.247822	1.084593
3	0.36154451	1.128077	1.054784
4	0.31310673	1.081422	1.040298
5	0.28005118	1.057609	1.03176
6	0.25565058	1.043529	1.02614
7	0.23668644	1.03439	1.022166
8	0.22139989	1.028061	1.019211
9	0.20873782	1.023464	1.016929
10	0.19802609	1.02	1.015115
11	0.18881046	1.017313	1.01364
12	0.18077226	1.015178	1.012416

1000 g/cm3

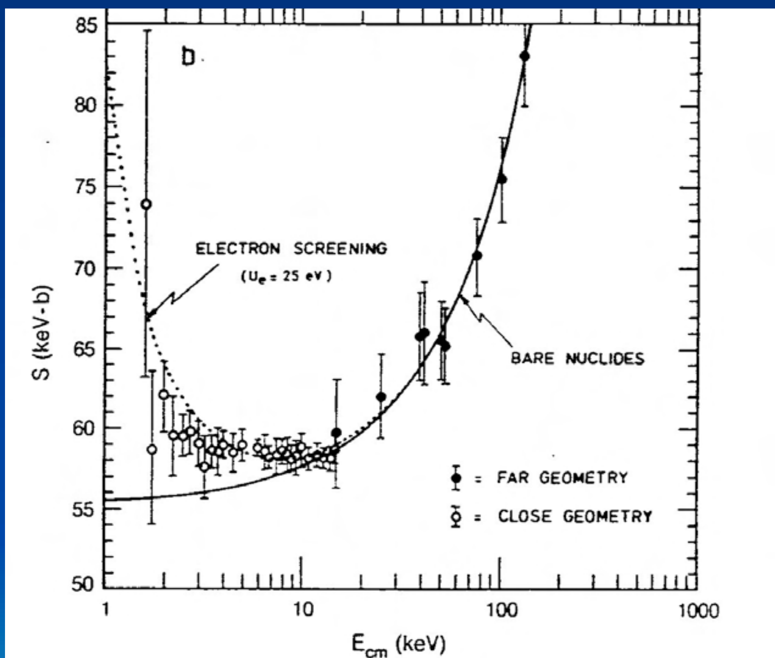
$^6Li(p,\gamma)^7Be$

For adiabatic limit
U_e = 0.182 keV

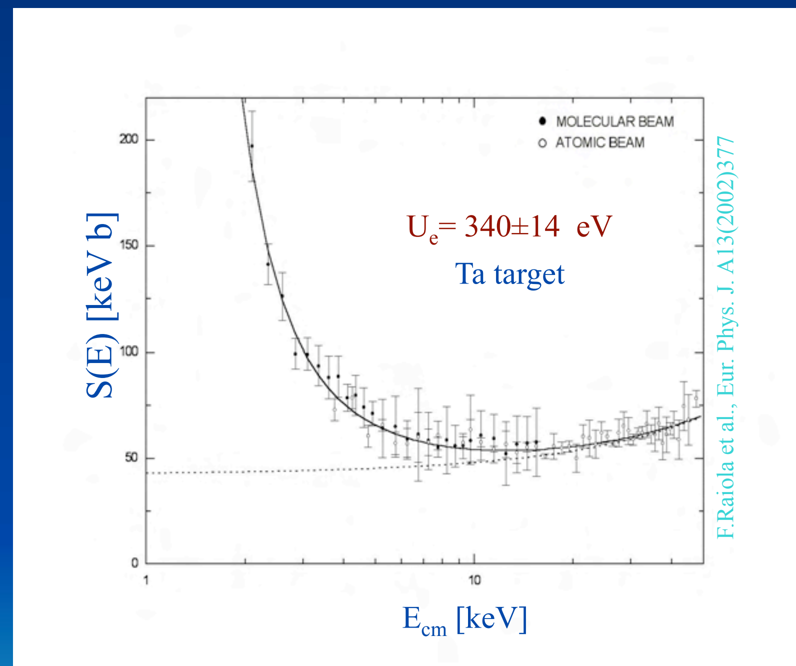
Slide borrowed from F.Raiola

d(d,p)t

Gas target



Deuterated solid target



U_e = 25 ± 5 [eV] (from U. Greife et al., 1995)

U_{ad} = 14 [eV] (≈ a factor 2 not known!!)

Suggests Debye model treatment

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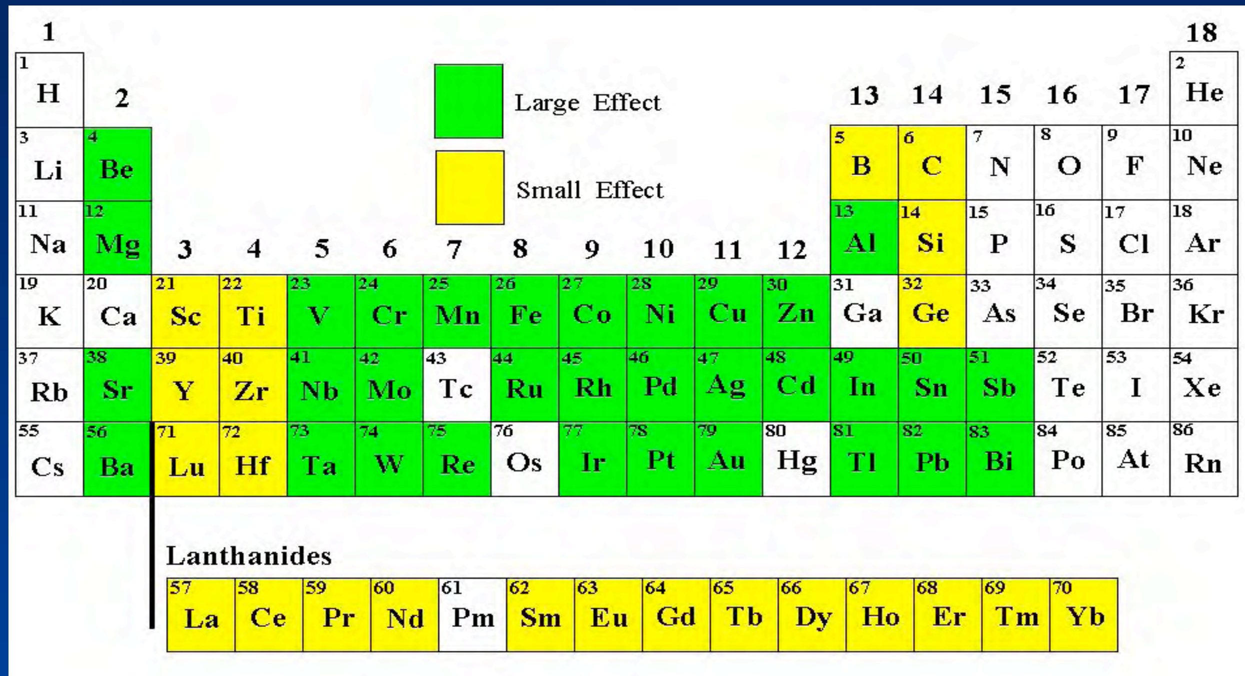
55 samples
in total
at room
temperature



F. Raiola et al.: Eur. Phys. J A19 (2004) 283

<u>FEATURES:</u>

- elements in same group show similar U_e values
- exceptions: group 13 (B = insulator) and group 14 (C, Si, Ge = semiconductors)
- large effect ~ 300 eV ⇔ metals with low “H solubility” (1/x)
  metallic character <u>retained</u> during implantation with D
- small effect ~ 30 eV ⇔ metals with large “H solubility”
  metallic character <u>lost</u> during implantation with D

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Additionally, temperature dependence was seen……..

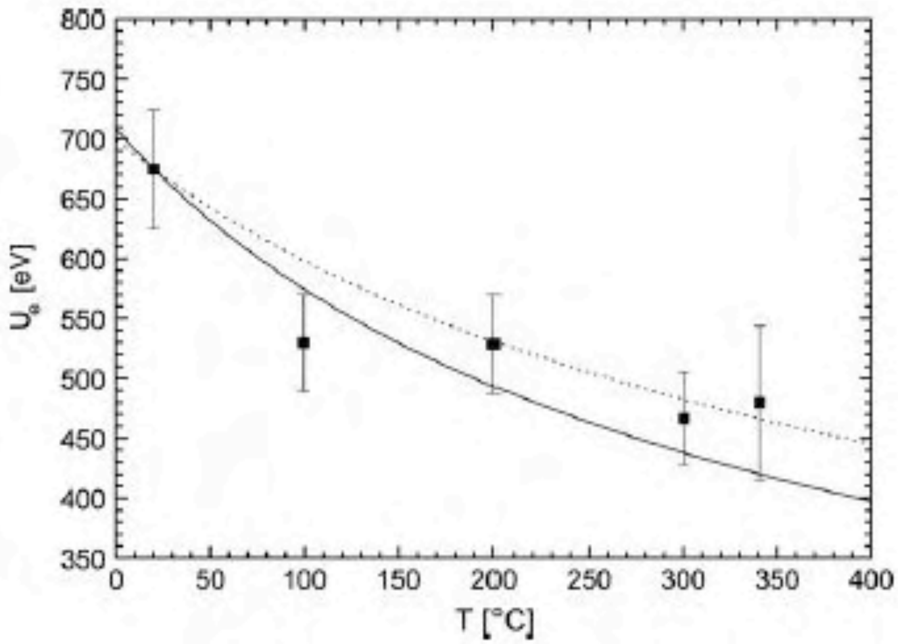

Fig. 10. The observed values $U_e(T)$ of d(d, p)t for a deuterated Pt foil are shown as a function of sample temperature T. The dotted curve represents the prediction of the Debye model and the solid curve includes the observed T-dependence of the Hall coefficient. The data represent the first observation of a temperature dependence of a nuclear cross section [45].

Slide borrowed from F.Raiola

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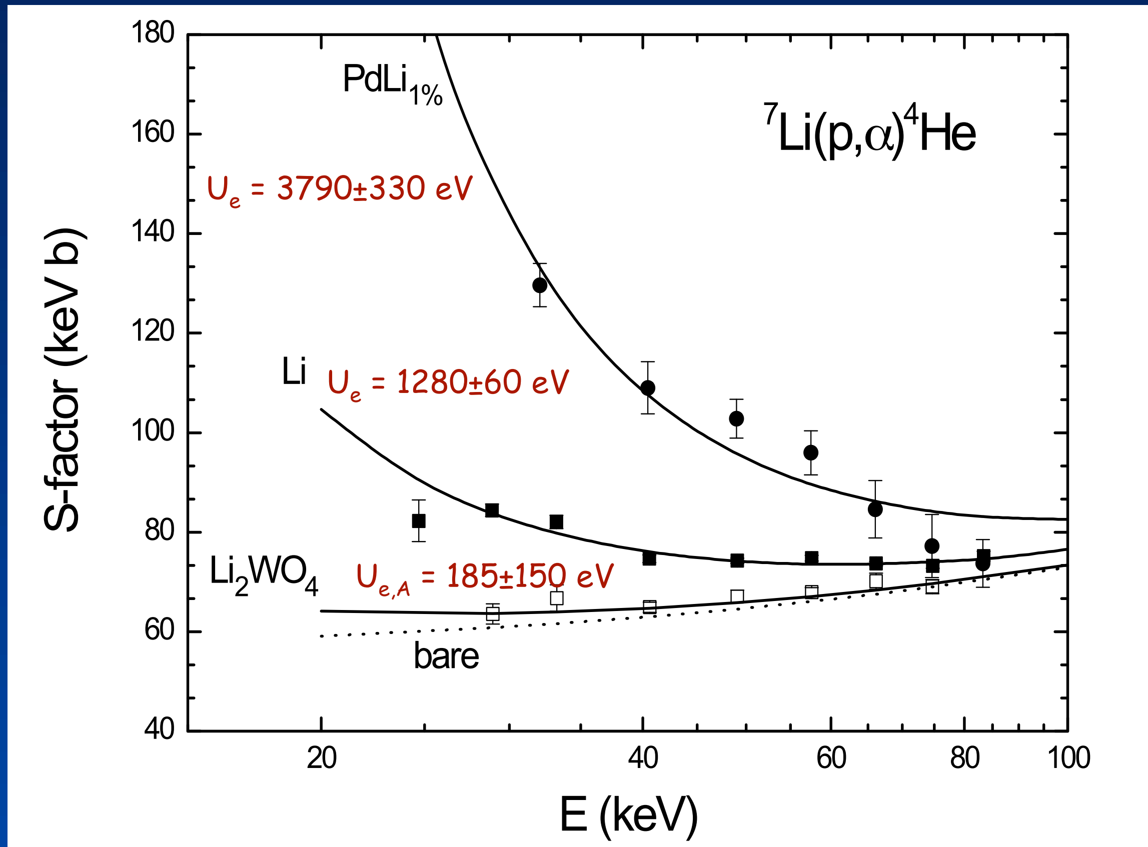


similar results obtained for $^6Li(p,\alpha)$

and

$^9Be(p,\alpha)^6Li$ and $^9Be(p,d)^8Be$ reactions

[D. Zahnow et al. Z. Phys. A359 (1997)211]

Electron screening in the laboratory only measured by one group and not that well understood so data from a different approach would be interesting

Yield estimates

We want to reach temperatures kT = 2-12 keV and 1000 g/cm^3 densities.

As I am no expert I used a tutorial: M.D. Rosen, Physics of Plasmas 6 (1999) 1690

Assumption: NIF 1.8 MJ of laser energy per shot

Driver efficiency:
Direct Drive 0.8; Indirect Drive 0.2

Efficiency of conversion of thermal energy to kinetic energy of imploding fuel:
Direct Drive 0.1; Indirect Drive 0.2

Energy per shot available to compress/heat
Direct Drive 8% of 1.8 MJ = 14.4 10^4 J; Indirect Drive 4% of 1.8 MJ = 7.2 10^4 J

Energy cost to compress fuel to high density
$\varepsilon_F = \alpha_{FD} * 3\ 10^5\ \rho^{2/3}$ J/g
with density 1000 g/cm3 and $\alpha_{FD} = 1$
$\varepsilon_F = 3\ 10^7$ J/g
for 10^{20} Hydrogen (0.166 mg)
$\varepsilon_F = 5\ 10^3$ J
more realistic ? $\alpha_{FD} \approx 4$?
$\varepsilon_F = 2\ 10^4$ J

This leaves for heating in Direct Drive 12.4 10^4 J; Indirect Drive 5 10^4 J

Yield estimates

Indirect Drive: left for heating $5\ 10^4$ J = $3.1\ 10^{23}$ eV
with 10^{20} protons and 10^{20} electrons
the energy per proton turns out to be 1.56 keV (kT = 1 keV)
this brings us the low end of the range of interest, with 10^{19} Hydrogen atoms we reach kT = 10 keV

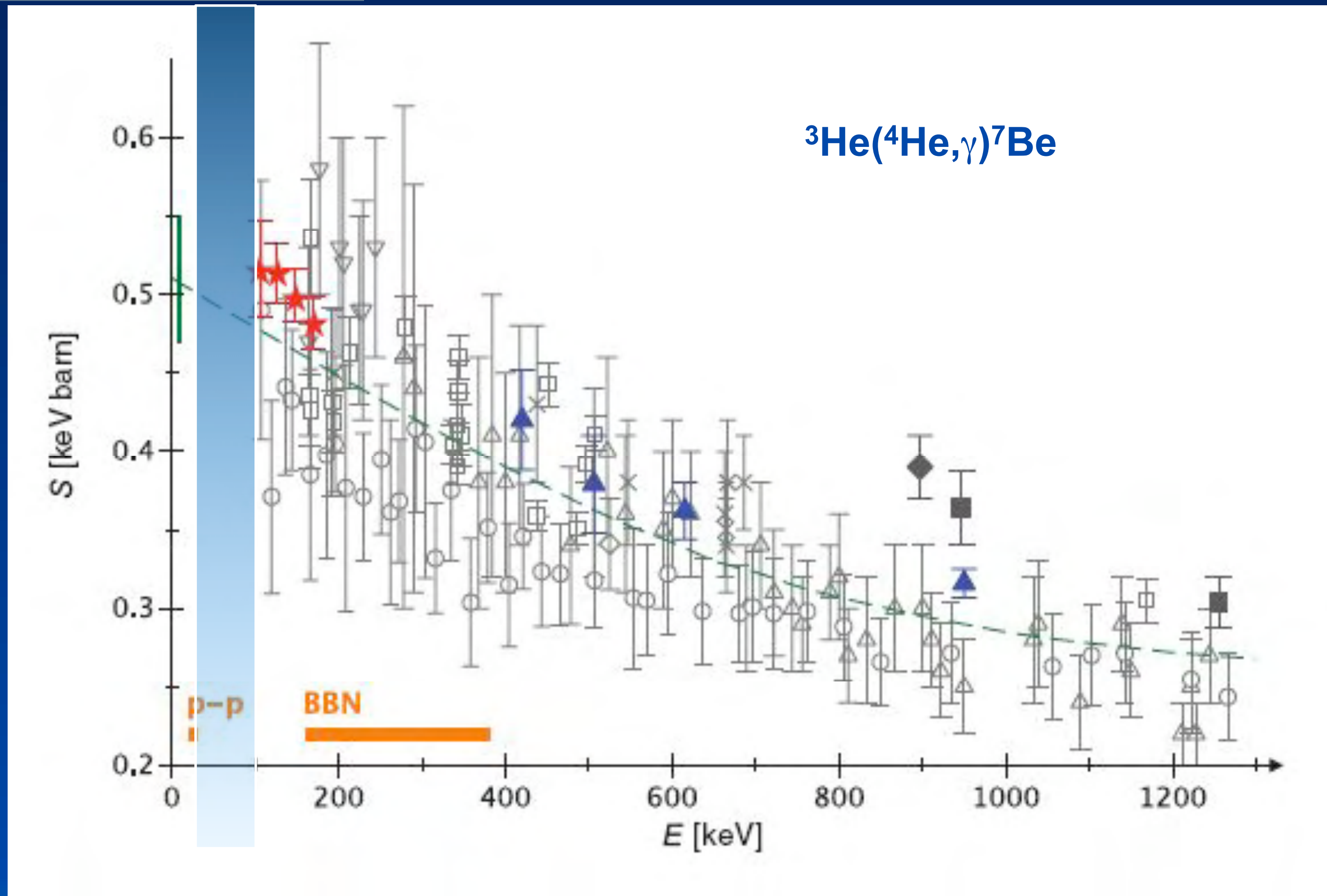
Direct Drive: left for heating $12.4\ 10^4$ J = $7.7\ 10^{23}$ eV
with 10^{20} protons and 10^{20} electrons
the energy per proton turns out to be 3.86 keV (kT = 2.57 keV)
this brings us the low end of our range of interest, with 10^{19} Hydrogen atoms we reach kT = 25.7 keV

As we have to distribute the energy on all protons, neutrons and electrons, we can only allow ourselves to mix in heavier elements in smaller amounts. The total number of protons, neutrons and electrons in the mix will have to be between 10^{19} and 10^{20} depending on what energy we want to achieve. We are lucky though that in the low energy regime, where out cross section tanks, we can allow ourselves a higher number of particles.

For simplicity the following estimates are therefore done with N(p,n,e) = $5\ 10^{19}$

I took the burn time of 1 psec from the dt capsules and a factor 20 compression,
this may be just a lower limit……..

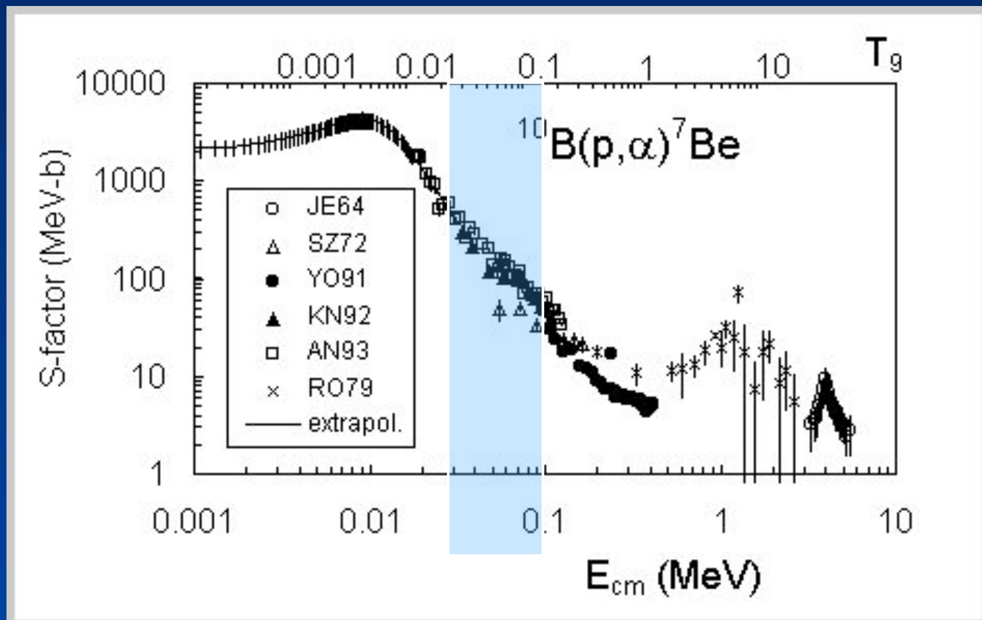
5 10^{18} ^{3}He and 4.2 10^{18} ^{4}He



kT [keV]	E_G [keV]	yield/shot
2	29.93	1.08E-03
3	39.22	4.80E-01
4	47.51	1.43E+01
5	55.13	1.59E+02
6	62.26	9.88E+02
7	69.00	4.24E+03
8	75.42	1.40E+04
9	81.58	3.86E+04
10	87.52	9.19E+04
11	93.26	1.96E+05
12	98.83	3.83E+05

Hard, but may be feasible with direct drive in the upper part of the interval

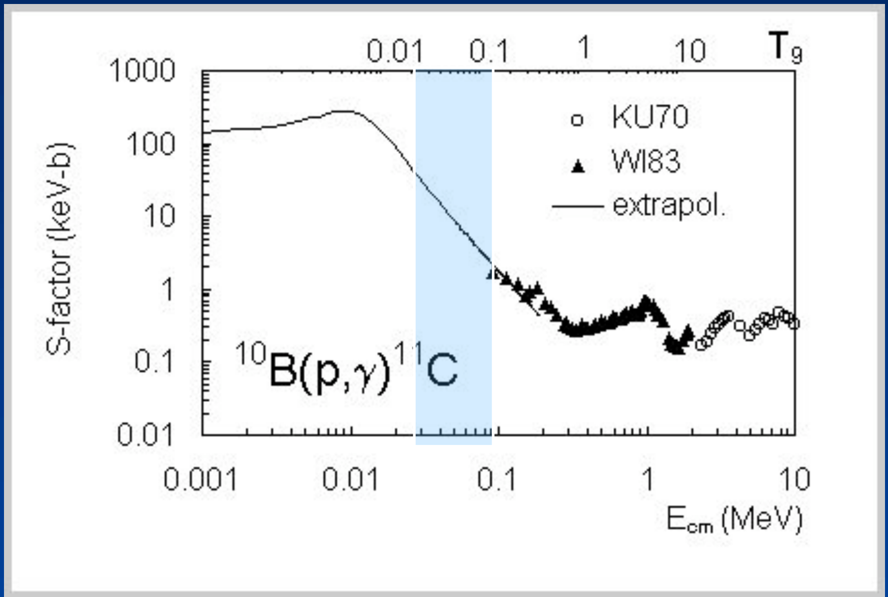
Another example: 1.25 10^{19} Hydrogen; 1.66 10^{18} ^{10}B



Good case for start to understand what we are doing; also electron screening if we can achieve high densities

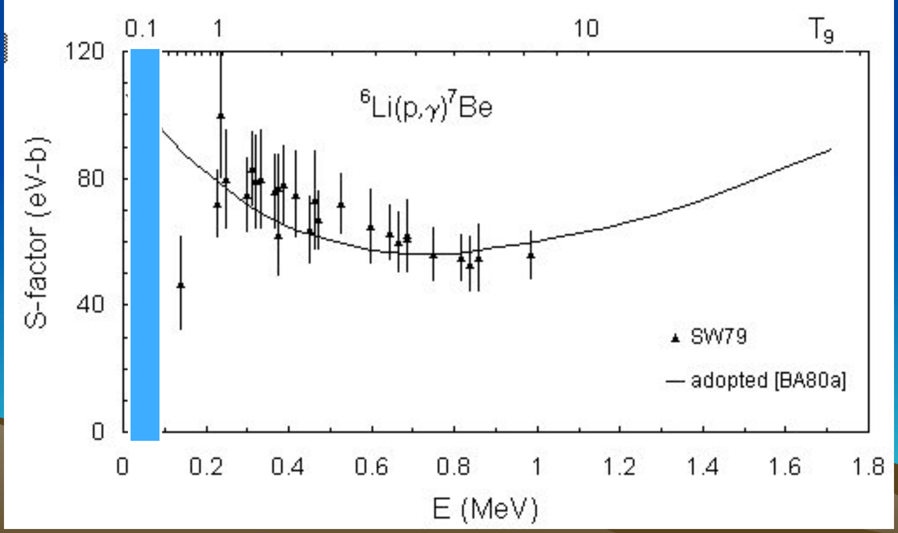
kT [keV]	E_G [keV]	yield/shot	f_{D-H} (2000 g/cm^3)
2	28.11194	4.34E+03	1.727748
3	36.83706	6.84E+05	1.346691
4	44.62492	1.64E+07	1.213283
5	51.78263	1.56E+08	1.148361
6	58.47518	8.61E+08	1.110972
7	64.80415	3.36E+09	1.087097
8	70.83764	1.03E+10	1.070742
9	76.62417	2.65E+10	1.058955
10	82.1998	5.96E+10	1.050125
11	87.59229	1.21E+11	1.043305
12	92.82357	2.26E+11	1.037907

Other possible cases with radioactive reaction product



$1.25\ 10^{19}$ Hydrogen; $1.66\ 10^{18}$ ^{10}B

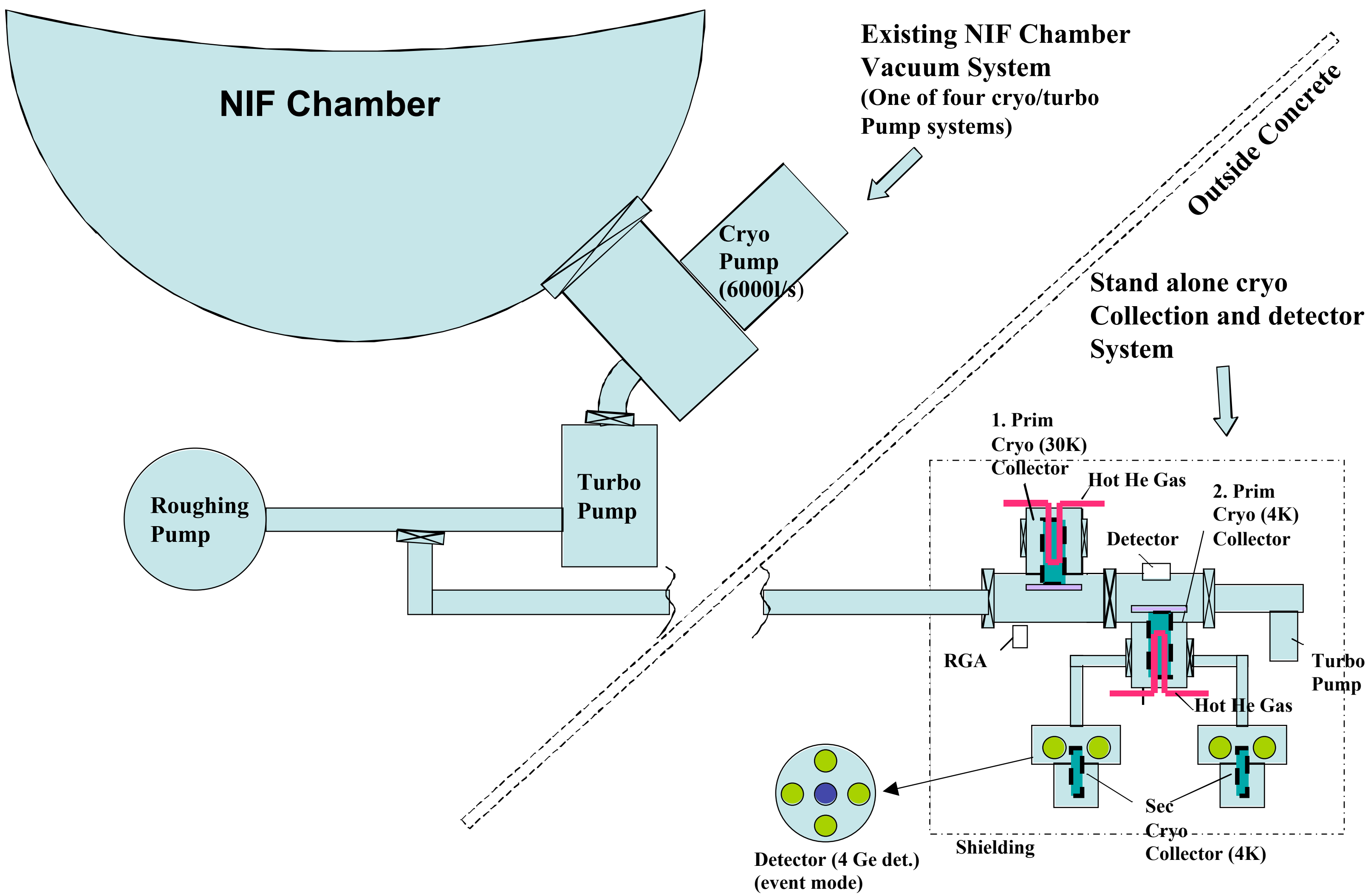
kT [keV]	yield/shot
2	4.34E-01
3	6.84E+01
4	1.64E+03
5	1.56E+04
6	8.61E+04
7	3.36E+05
8	1.03E+06
9	2.65E+06
10	5.96E+06
11	1.21E+07
12	2.26E+07



kT [keV]	yield/shot
2	2.15E+03
3	6.77E+04
4	5.86E+05
5	2.69E+06
6	8.55E+06
7	2.14E+07
8	4.56E+07
9	8.60E+07
10	1.48E+08
11	2.38E+08
12	3.62E+08

How?

Radchem Gas Collection System using existing NIF Chamber Vacuum System



We have to get the stuff out to get low background measurements!

nuclear physics @ csm

^{7}Be:
$T_{1/2}$ = 53.3 d
γ energy: 0.478 MeV (10%)

Relatively long half life
and
only 10% gamma emission
translates to low sensitivity:

Still possible as reaction
product 10B(p,a)7Be
or
as tracer to determine
collection efficiency.

Can be produced at ALEXIS
(actually is byproduct of
neutron beam production)

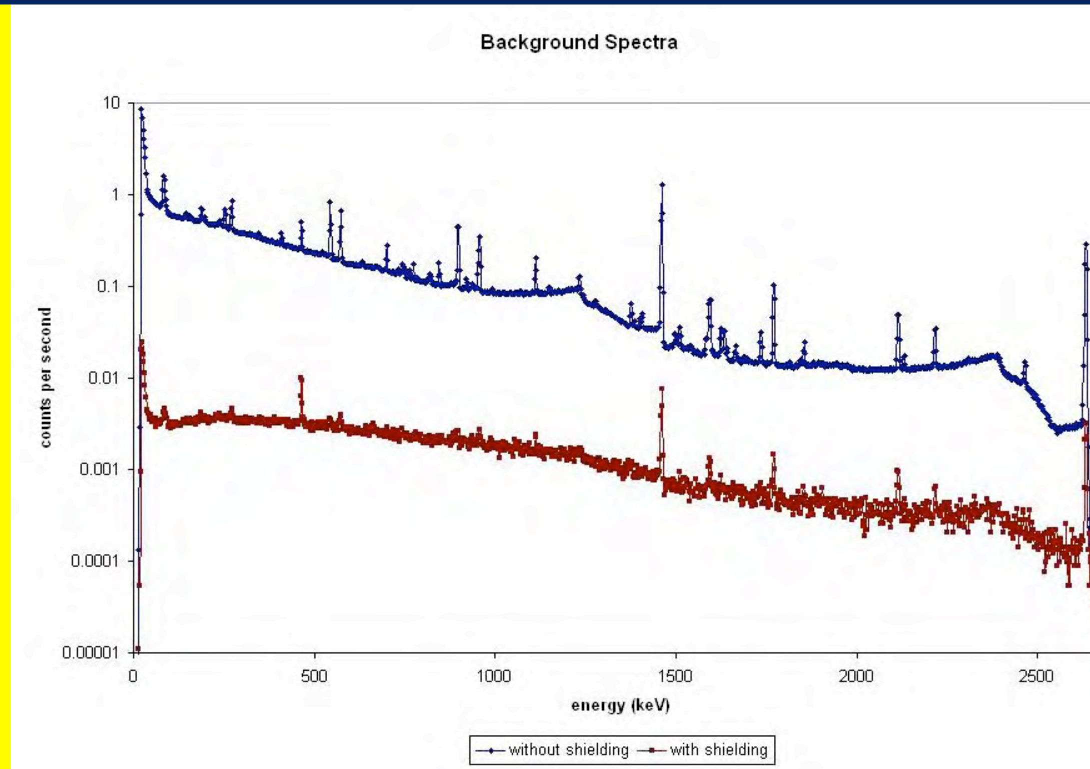


Fig. 1: Background spectra of a 20% Germanium detector unshielded (blue) and shielded (~10 cm low background lead) at the Colorado School of Mines. The low energy background peak in the shielded configuration is at 460 keV and will not interfere with our 478 keV peak.

For our 20% (compared to a 3" x 3" NaI) Germanium detector, we assume in the following: a 1 % detection efficiency for the 478 keV gamma photon at minimal distance to the detector surface. Fig. 1 shows background spectra with unshielded (background situation roughly like for in-situ measurement) and shielded (low background lead) configurations with the Colorado School of Mines detector.

In our area of interest (5 channels added up to cover the approximate 478 keV peak region) we saw a background of 0.02 counts per second in the shielded configuration. Performing a 10000 second long measurement of the wear debris, we would encounter a b ackground of 200 counts with a statistical variation of $\sigma = \mathrm{sqrt}(200) = 15$ counts. In order to de termine the possible resolution we assume that a 2σ signal above background is detectable translating into 30 counts in 10000 seconds or a count rate of 0.003 counts/sec. Factoring in the detector efficiency results in 0.3 gamma emissions/sec as our resolution limit. This requires 3 Bq activity of our wear debris or a ^{7}Be content of $2*10^{7}$ atoms.

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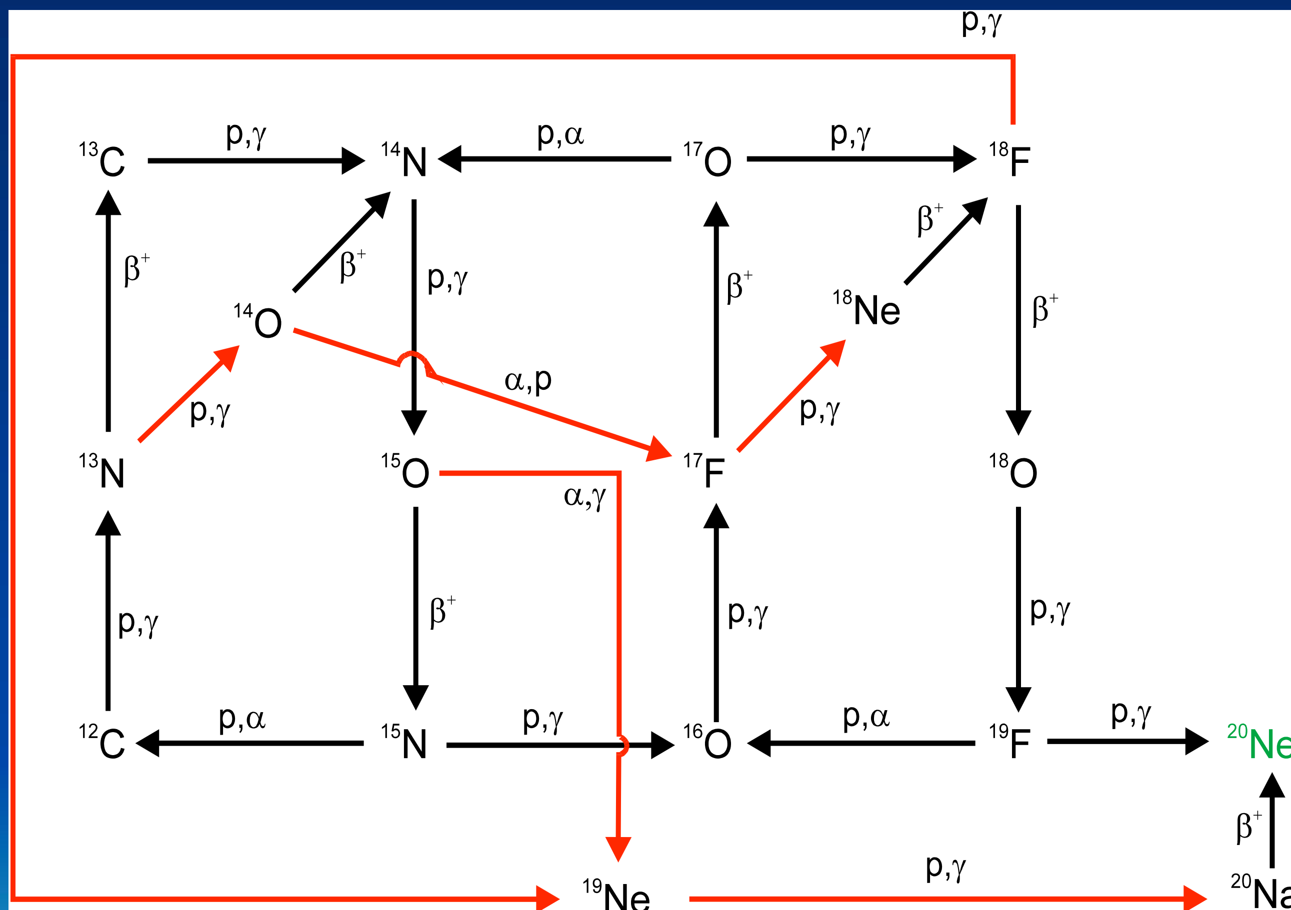
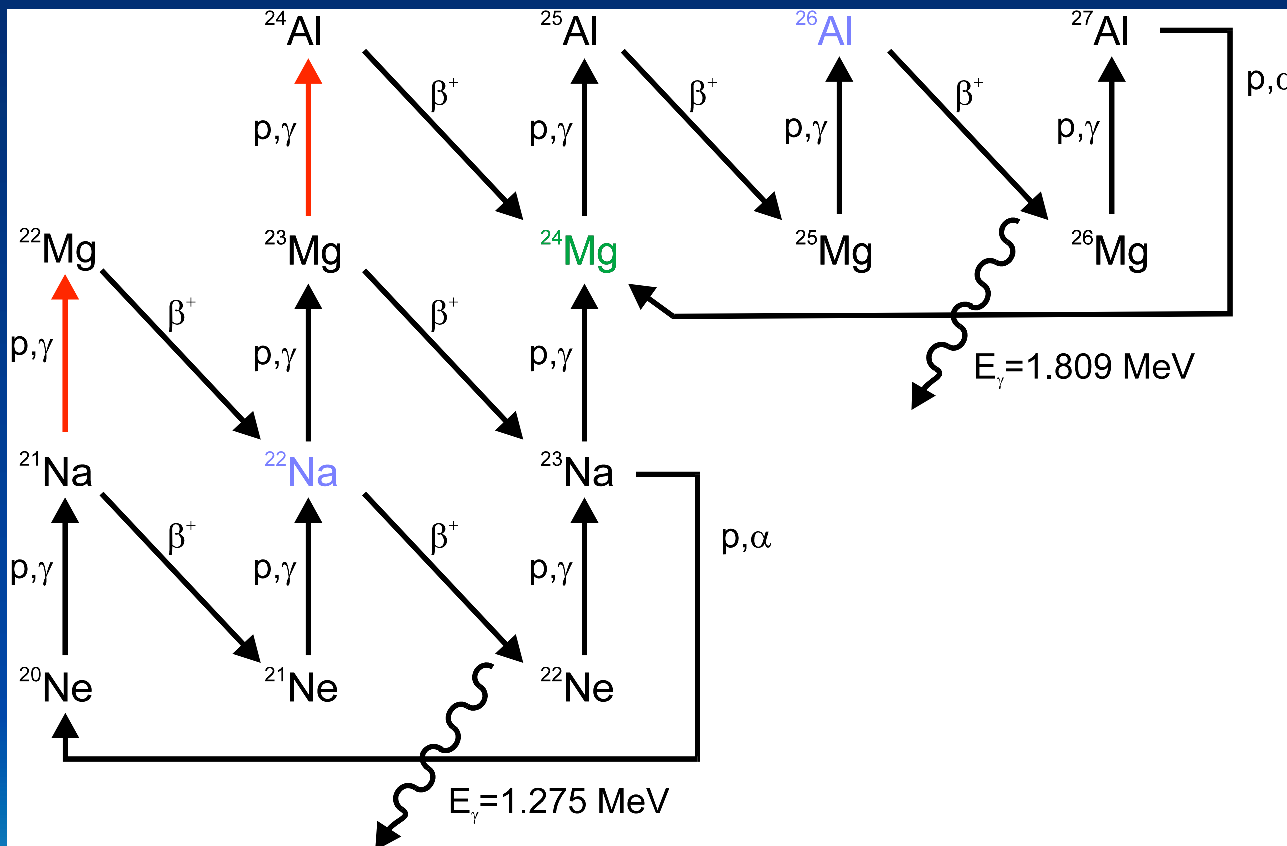
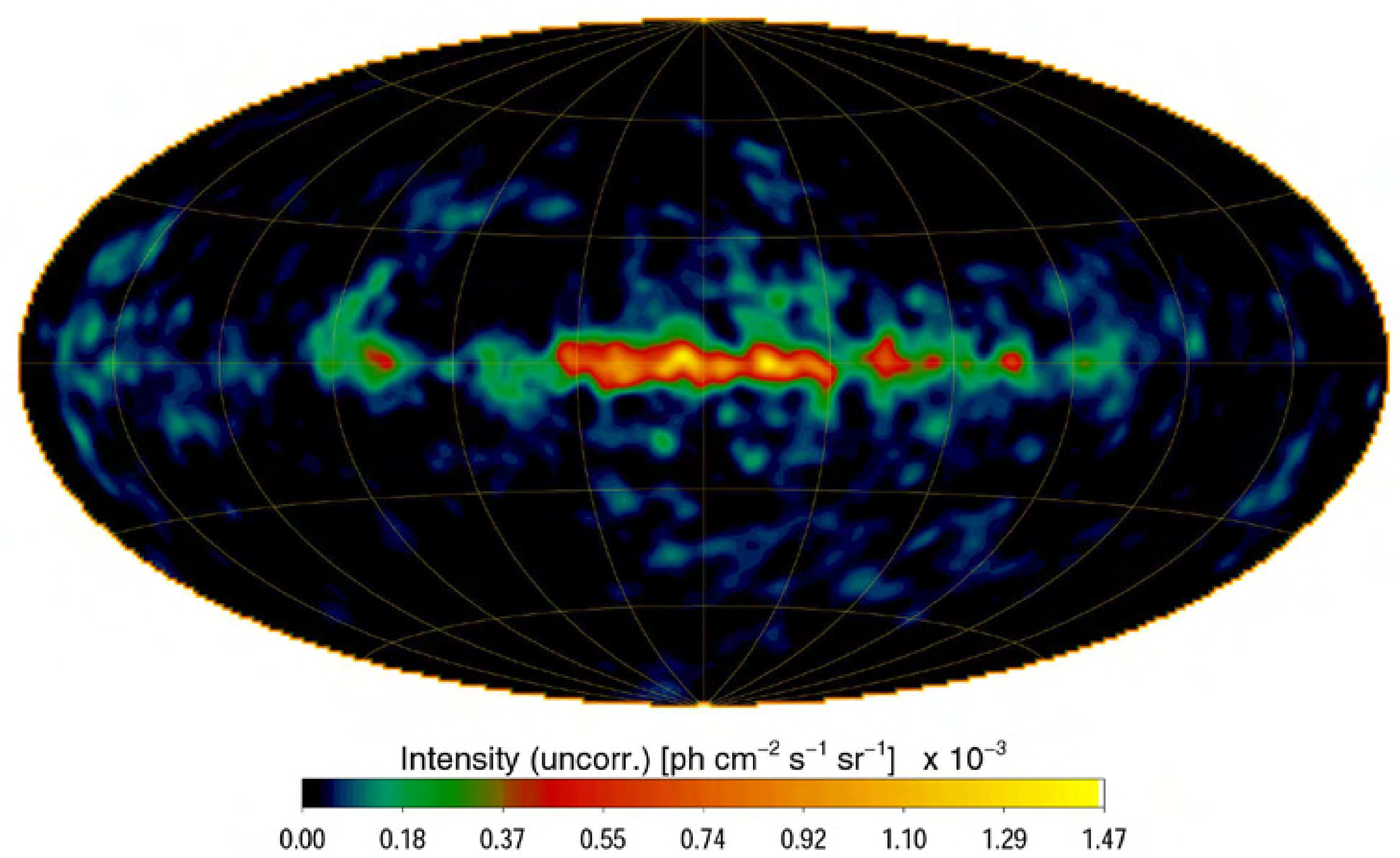
The hot CNO cycles

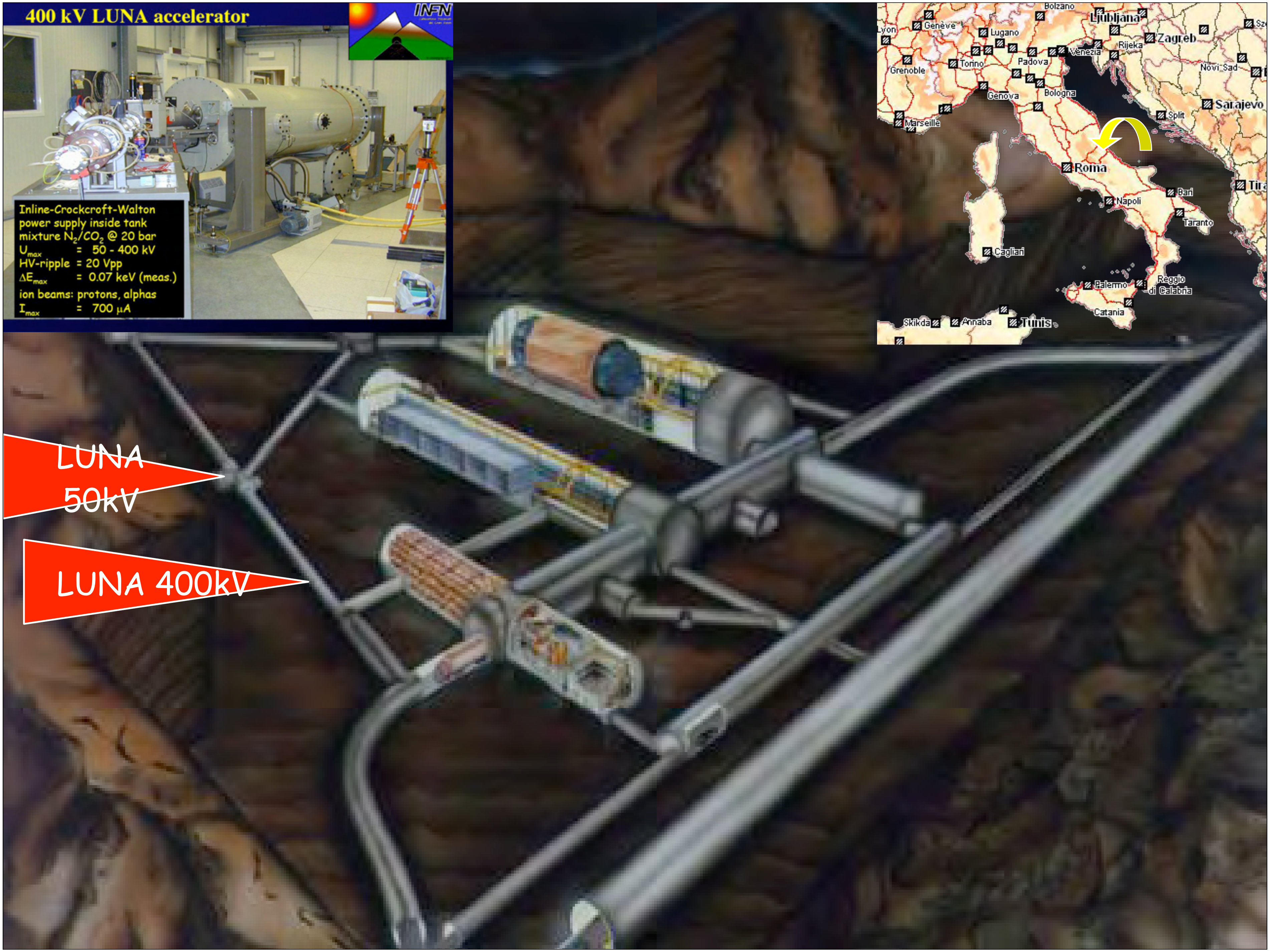


Production of the cosmic γ-ray sources ^{22}Na and ^{26}Al

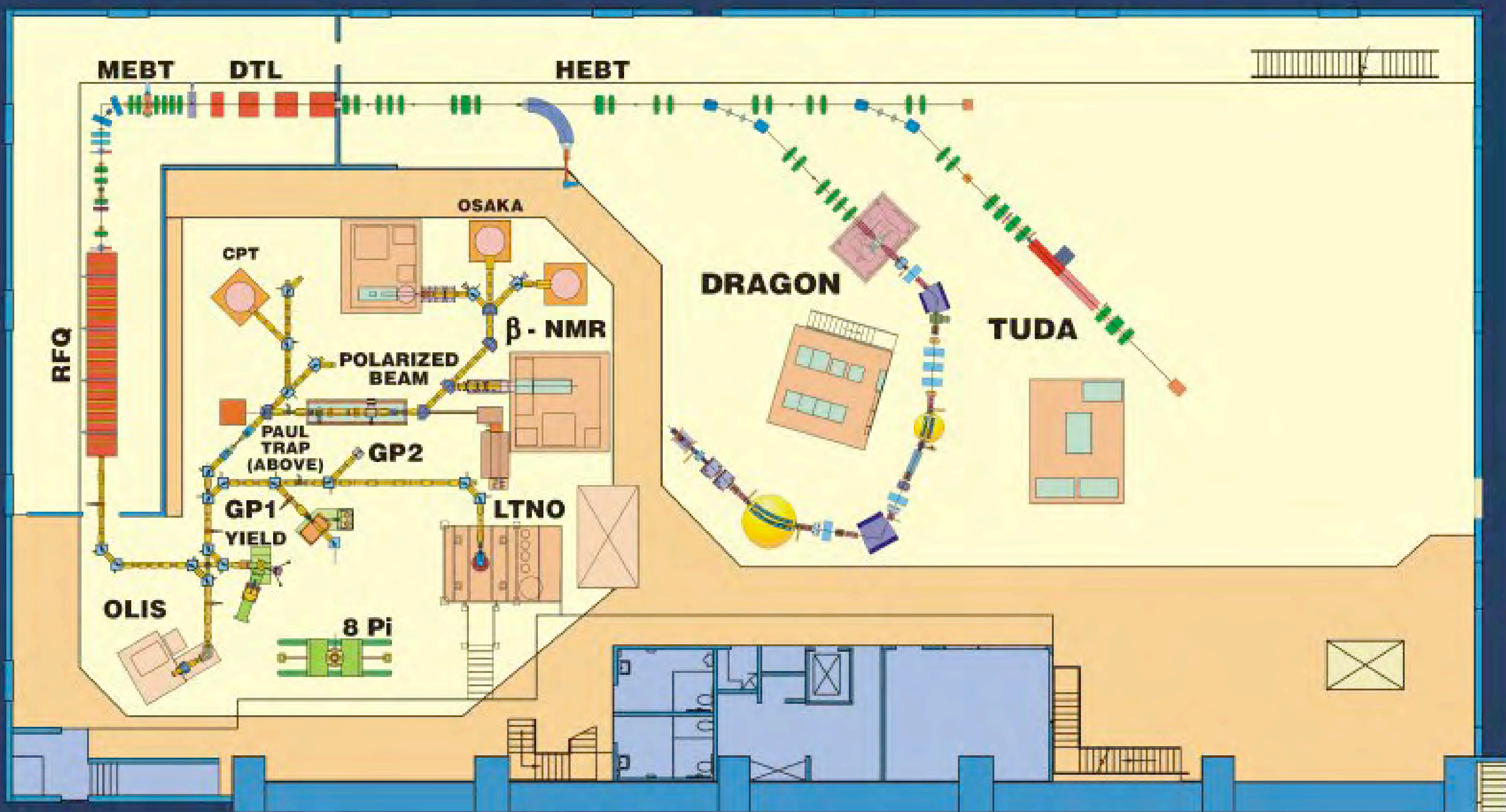


Aluminum-26 in the universe




400 kV LUNA accelerator
INFN
Inline-Crockcroft-Walton
power supply inside tank
mixture N_2/CO_2 @ 20 bar
U_{max} = 50 - 400 kV
HV-ripple = 20 Vpp
ΔE_{max} = 0.07 keV (meas.)
ion beams: protons, alphas
I_{max} = 700 μA
Bolzano
Ljubljana
Lyon
Genève
Lugano
Zagreb
Venezia
Rijeka
Grenoble
Torino
Padova
Novi Sad
Genova
Bologna
Sarajevo
Marseille
Split
Roma
Bari
Napoli
Taranto
Cagliari
Palermo
Reggio di Calabria
Catania
Skikda
Annaba
Tunis
LUNA 50kV
LUNA 400kV

ISAC EXPERIMENTAL HALL



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1.25 10^{19} Hydrogen; 1.39 10^{18} ^{12}C

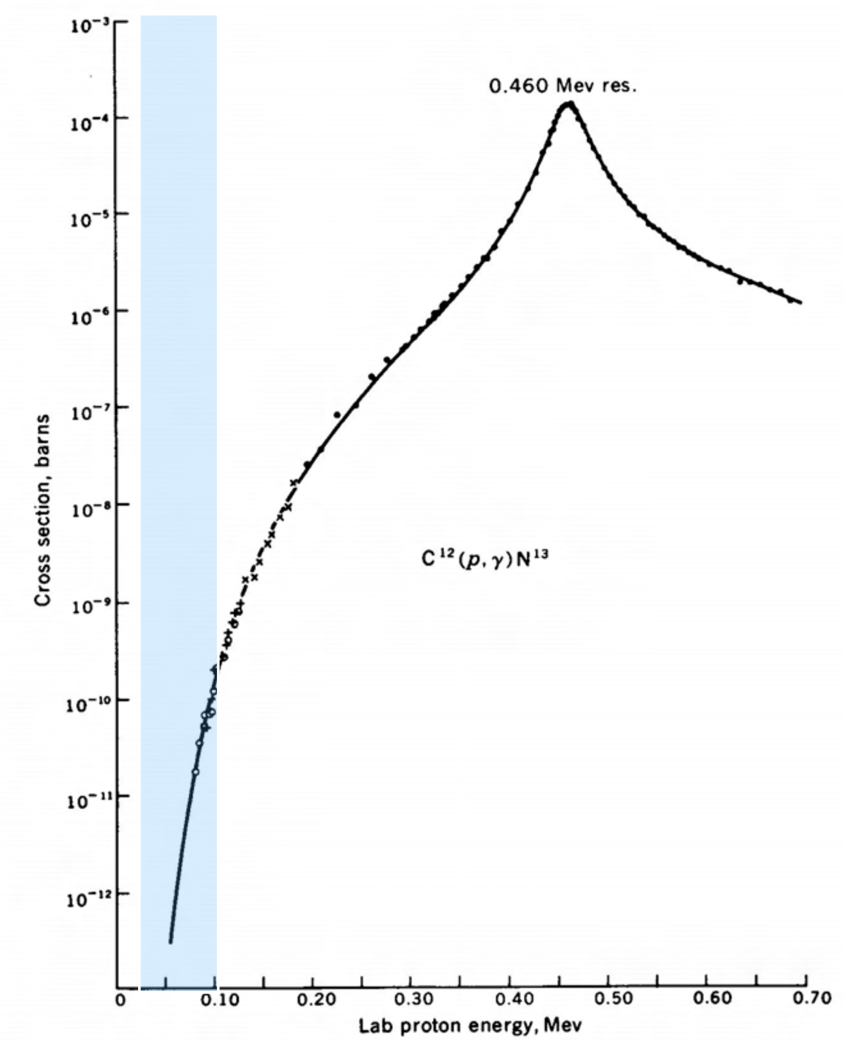
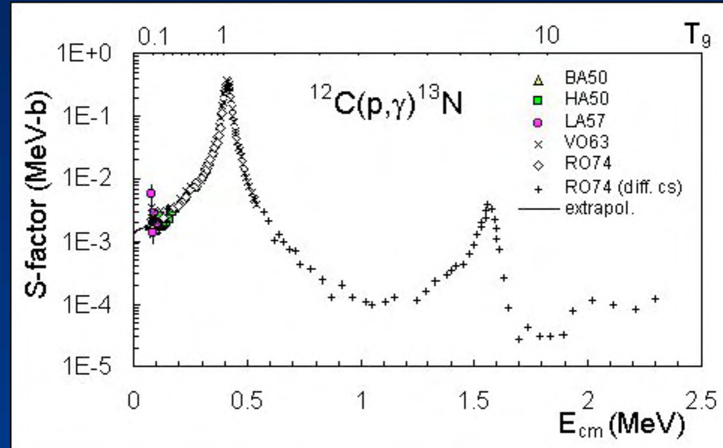


Fig. 4-4 The measured cross section for the reaction $C^{12}(p,\gamma)N^{13}$ as a function of laboratory proton energy. A four-parameter theoretical curve has been fitted to the experimental points. An extrapolation to $E_p = 0.025$ Mev, which is an interesting energy for this reaction in astrophysics, appears treacherous. (*Courtesy of W. A. Fowler and J. L. Vogl.*)



kT [keV]	yield/shot
2	1.29E-04
3	4.19E-02
4	1.58E+00
5	2.08E+01
6	1.47E+02
7	7.00E+02
8	2.52E+03
9	7.45E+03
10	1.89E+04
11	4.25E+04
12	8.71E+04

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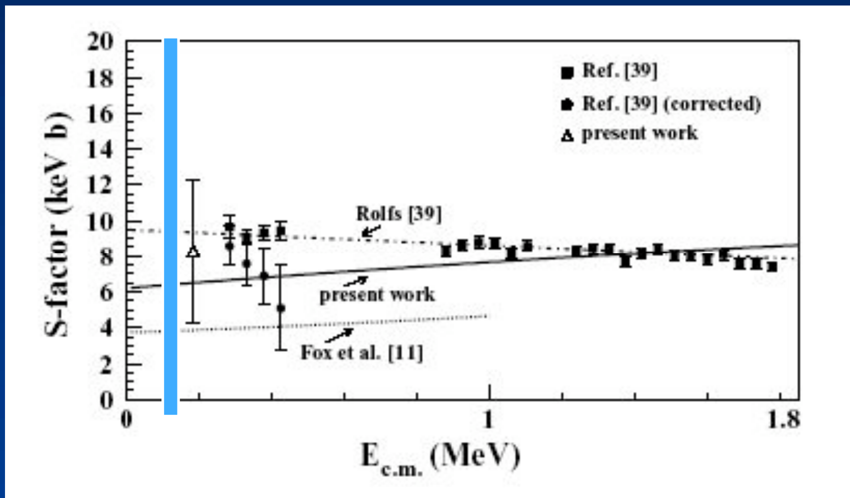
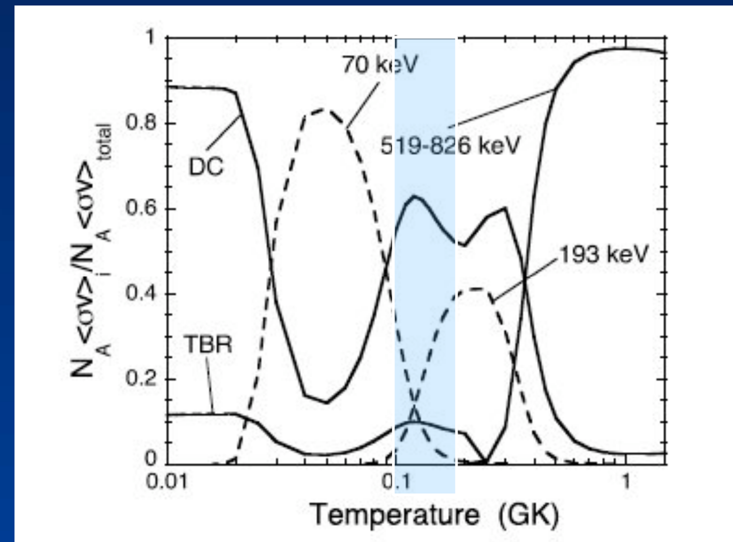
$^{17}O(p,\gamma)^{18}F$ 1.25 10^{19} Hydrogen; 1.00 10^{18} ^{17}O





kT [keV]	yield/shot
2	2.63E-08
3	3.24E-05
4	2.84E-03
5	6.80E-02
6	7.63E-01
7	5.23E+00
8	2.56E+01
9	9.75E+01
10	3.08E+02
11	8.42E+02
12	2.05E+03

It is getting difficult………

What else?

Other viable (radioactive reaction product produced in sufficient quantities at NIF ion temperatures) reactions with the same interplay of direct capture and narrow resonances at low (never before measured energies) are: $^{21}Ne(p,\gamma)^{22}Na$ (a very strong candidate due to unmeasured resonance at 94 keV), $^{22}Na(p,\gamma)^{23}Mg$ (difficult due to radioactive target), $^{24}Mg(p,\gamma)^{25}Al$ and $^{25}Mg(p,\gamma)^{26}Al$ (reaction to $^{26}Al_m$ can be detected).

All these reactions rely on low energy resonances for yield and can be measured in the range 100 - 140 T_6

Conclusions:

• I do not understand enough about the conditions we will find in NIF shots to allow me to go from estimates to predictions

• We need to figure out the design of capsules that contain mainly Hydrogen with an admixture of about 10% heavier isotopes

• We need to get numbers for temperatures, densities and burn times that can be achieved

• What are estimates for the reproducibility of NIF shots

• What will be the collection and detection efficiencies of the Nuclear Diagnostic systems (backgrounds?)

• We need to figure out what critical properties we need to know and have overlooked so far……….

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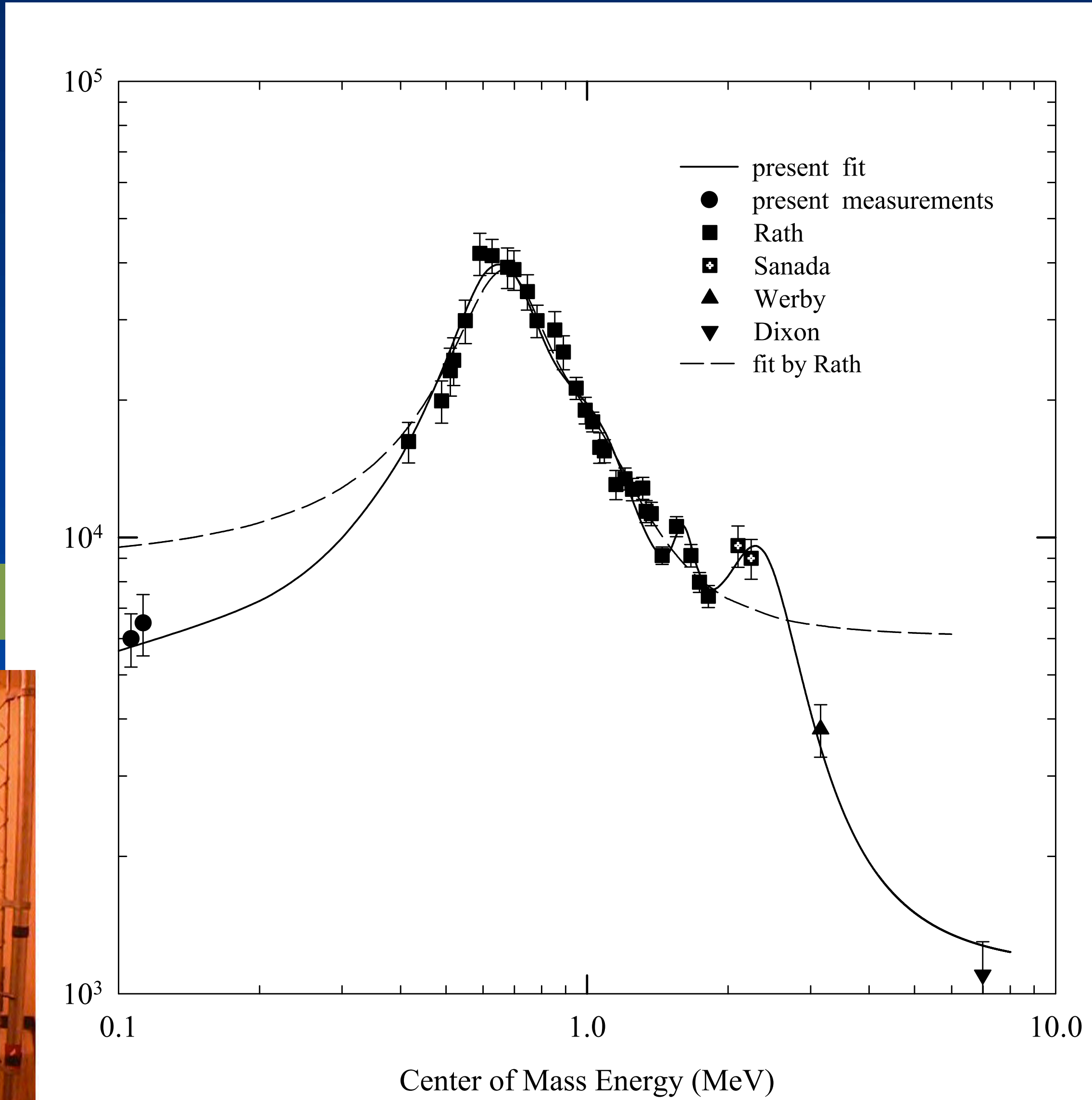
Problems with extrapolated cross sections…….

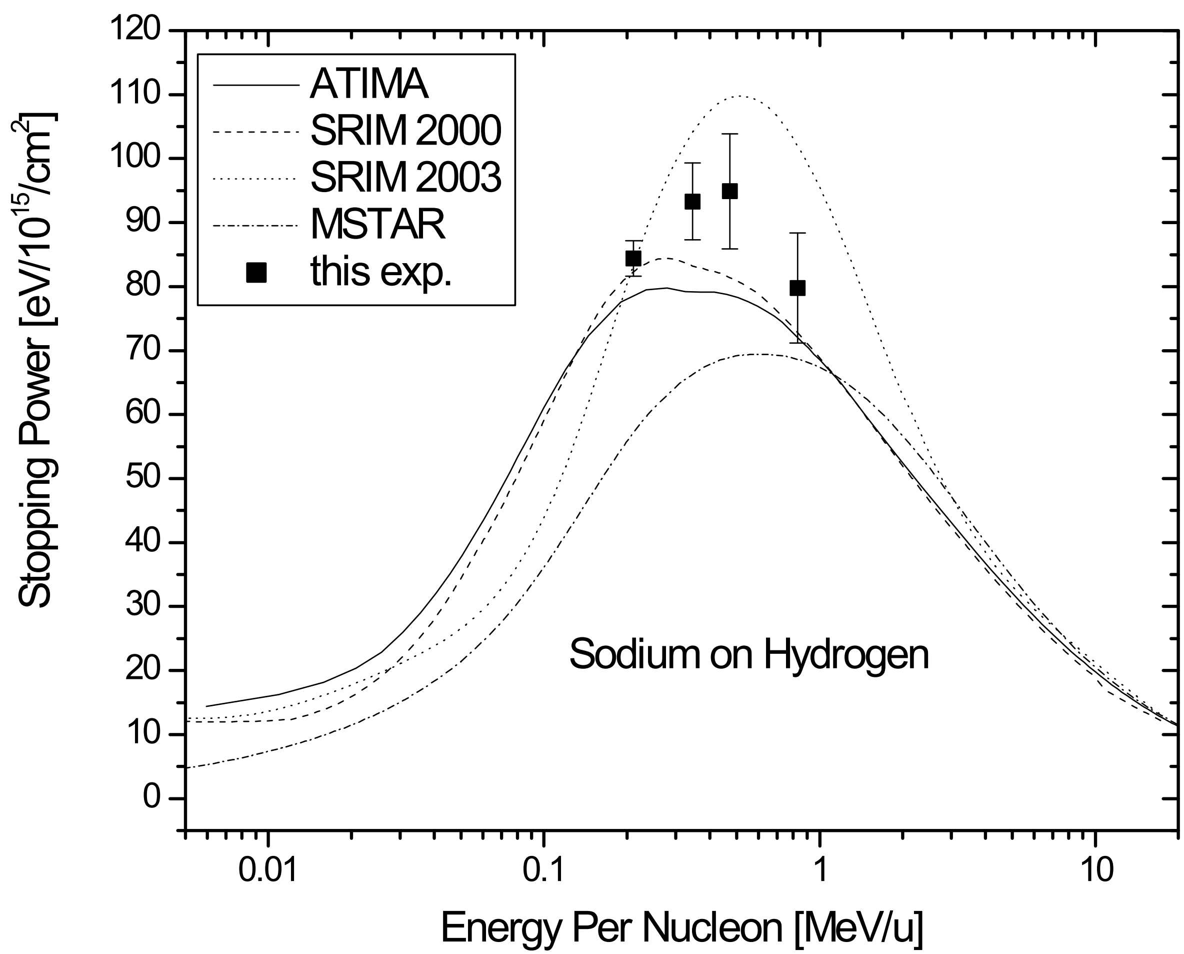
$^7Li(^3He,p_0)^9Be$

CSM 180 kV ion accelerator



Stopping in gaseous targets.........

Stopping Power dE/dx



Stopping at very low energies……

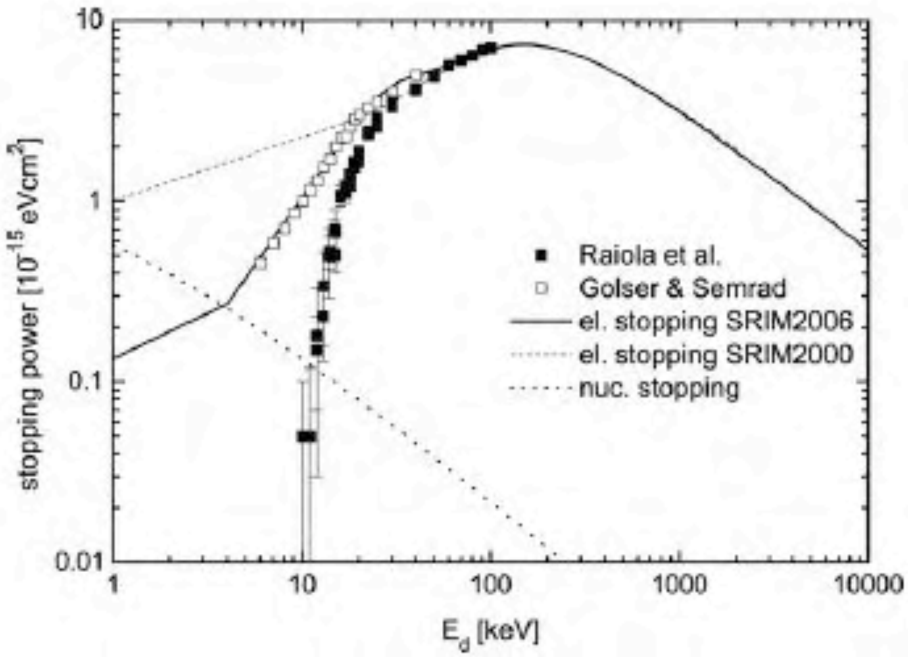


Fig. 11. Total stopping-power data of deuterons in ^{3}He gas at energies below the Bragg peak [58,59]. The dashed curve is the prediction of a compilation (SRIM-2000 [57]), based on data at energies near and above the Bragg peak, while in the recent version of the compilation low energy data were taken into account (solid line). The dotted curve represents the predicted nuclear stopping power.

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